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Estimating Foliage Biomass of White Fir and Douglas-Fir Trees in the Lincoln National Forest

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ESTIMATING FOLIAGE BIOMASS OF WHITE FIR AND DOUGLAS-FIR TREES IN THE LINCOLN NATIONAL FOREST

By

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SUMMARY

Foliage biomass was collected from 18 trees, included 6 Douglas-fir, 6 Douglas-fir infected with dwarf mistletoe and 6 white fir trees. Foliage biomass was determined by correlating branch diameter and foliage biomass on 10% of the branches per tree. These results were used to test other biomass estimation methods. Diameter inside bark at ground level was the best estimate ($R^2 = 0.99$), while DBH was also a good estimator ($R^2 = 0.94$). Importance sampling using branch diameter also seems to have an excellent potential in estimating foliage biomass. With importance sampling, sampling should be restricted to that proportion of the main bole between 30 and 50% of the total tree height. DBH seemed to be the easiest way to determine foliage biomass, it is a good estimate especially when a quardratic is used. Importance sampling might be more consistant if needle biomass on the sampled branches is weight instead of estimated.

INTRODUCTION

Forest productivity is a critical issue facing forest managers. The primary driving force in productivity is the foliage biomass which fixes atmospheric carbon into woody biomass. Many factors can influence not only the foliage biomass, but also the ability of the foliage to function photosynthetically. Among these factors are species, site, and environmental stresses including attack by other organisms.

While foliage biomass is a strong determinant of stand production it is also a key component in population dynamics of defoliating insects. One example include the western spruce budworm *Choristoneura occidentalis* (Freeman) attacking Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) and white-fir (*Abies concolor* (Gordon & Glendinning) Hoopes) in the southwestern United States. Western spruce budworm has a preference for current year's foliage and is dependent on phenological stage of bud break, needle growth, rate of growth and rate of maturation. Models predicting insect dynamics, like the Prognosis Spruce Budworm Modeling System Model, need foliage biomass as an input (Sheehan et al., 1987).

Little is known about the productivity and foliage biomass dynamics of Douglas-fir and white fir growing in southern New Mexico, where western spruce budworm outbreaks are common (Swetnam and Lynch 1989, Brookes et al. 1987). An additional factor important in southern New Mexico is Douglas-fir dwarf mistletoe (*Arceuthobium douglasii*), which depresses productivity and increases plant susceptibility to defoliating insects (Filip and Parks 1987). In addition, disease or abiotic stress such as drought or shade results in the shedding of older needles. Premature needle shedding can reduce subsequent growth indirectly through reduced photosynthesis.

The objective of this study was to determine the foliage biomass of white fir and Douglas-fir trees in the Lincoln National Forest. An additional objective was to determine the effect of dwarf mistletoe on foliage biomass allocation within Douglas-fir trees. These results will be used to validate the Prognosis model for the Southwest Region.

METHODOLOGY

Twelve Douglas-fir trees, six infected with dwarf mistletoe and six without infection, and six white fir trees were harvested between the middle of August and the beginning of October 1990. Trees were harvested off Sixteen Springs Canyon road on a 4 km stretch on the north facing slope of James Ridge (Appendix I). Tree height ranged between 6.85 and 26.40 m with DBH between 11.2 and 48.6 cm (Table 1). Care was taken to select trees with relatively uniform crowns. Measurements prior to felling included tree height, crown diameter, crown ratio, BA, DBH, and similar measurements on trees growing within a 5 m radius of the sample tree. Of the associated species, DBH, distance from the original tree, compass angle as related to the to be harvested tree and species was recorded. These measurements were taken to satisfy requirements for Moeur's equations (Moeur 1981). An additional requirement of Mouer, tree age, was determined in the laboratory.

After felling, all lateral branches originating from the bole were cut. Height of the branch and bole diameter at every branch were recorded prior to cutting. Branches were cut and numbered; the diameter and length of each branch were measured. Approximately 10% of the branches were selected at random for further analysis in the laboratory. These branches were packed in individual paper bags and dried. Disks of every branch were collected for age and sapwood determination in the future. A segment of the bole (disk) was cut at the base and at 5 meter increments up the main stem for age determination.

Samples were dried at 75°C for approximately two weeks. Needles were removed by hand and the total amount of needles from a branch were weighed. The data was entered in a spread sheet package (Quatro-Pro vers. 2), in order to use importance sampling for biomass determination (Valentine et al. 1984). Data entered for each branch included: bole diameter at branch position, branch diameter and actual or estimated needle biomass (Appendix II).

Probability formulas as prescribed by Valentine et al. (1984) were used to estimate total tree biomass. Estimated needle biomass for the non-sampled branches was determined through correlation. Previously we had determined that there was a close relationship between needle biomass and both branch diameter and branch length (Mexal and Briedé, 1990). Calculated total tree biomass, determined with importance sampling, were entered in each file, after which an estimated biomass profile for each tree could be graphed. After examination of these graphs, it was decided to normalize the data, by assuming that the actual needle weight and tree height were 100%. Subsequently, trees per group were pooled and biomass distribution profiles were analyzed by canopy tenths.

Additional analysis conducted were (1) needle biomass distribution by crown tenths, (2) needle biomass as a function of DBH, (3) needle biomass as a function of diameter inside bark at ground level (DIB), (4) needle biomass as a function of current year's bole increment, (5) needle biomass as a function of the bole increment of the current sapwood area (5 or 7 years depending on the species), (5) needle biomass as a function of tree height, (6) multiple regression models of the above measurements for needle biomass, (7) estimation of current nad last years' biomass, and (8) the estimation of chlorophyllus biomass using the equations of Moeur (1981). In the Moeur equations, white fir was treated as grand fir.

RESULTS

Tree age ranged between 37 and 87 years, with heights between 6.85 and 26.40 m and DBH between 11.2 and 48.6 cm (Table 1). Average tree heights (± se) were 12.67 (± 2.93), 10.84 (± 1.79) and 14.56 (±8.23) m for Douglas-fir without mistletoe infection, Douglas-fir with mistletoe infection and white fir respectively. Live crowns extended 87.6% (±3.2) of the tree length.

Branch needle biomass for individual branches was determined through regression and entered as individual formulas (Table 2, Appendix II). Branch diameter explained 56, 47 and

68% of the variability in needle biomass of a branch for Douglas-fir without mistletoe infection, Douglas-fir with mistletoe infection and white fir respectively. Adding branch length to the model did not improve the correlation and multi co-linearity was found between branch length and branch diameter. This can also be concluded from the strong correlation between branch diameter and branch length (Table 2).

Using the branch diameter to estimate the total biomass on the trees, we found that total needle biomass ranged between 5.38 and 103.58 kg (Table 3). Table 3 also shows comparisons with Mouer's methodology (Mouer 1981) for needle biomass estimation (individual calculations in Appendix III). On the average Mouer's, equations overestimated needle biomass by 46.2, 32.7 and 92.5% for Douglas-fir without mistletoe infection, Douglas-fir with mistletoe infection and white fir respectively (Table 4). Adjustment of Mouer's correlation coefficients might be warranted if so desired; however, other convincing relationships between the measured tree parameters and foliage biomass were found (Table 4). DBH and DIB explained up to 99% of the variability in needle biomass of the trees (Fig. 1, 2). Using a quadratic formula and combining the three treatments (plant types), DIB explained 98% of the variability in needle biomass (Fig. 3). Combining the data collected from last winter's trees with the present data, DBH and foliage biomass had a quadratic relationship with an $R^2 = 0.94$ (Fig. 4, 5; no DIB measurements were taken on the winter trees). The only other significant improvement was seen in white fir and the sapwood area of the last seven year's growth increment ($R^2 = 0.96$; Table 4; Fig. 6, 7). Multiple regression models did not seem to improve the correlations.

Individual branch needle biomass was used in the importance sampling scheme to determine biomass of the trees (Fig. 8 through 16; see Appendix II for the calculations). Data showed evidence of slight under estimation in the lower part of the canopy, while branches in the top of the canopy tended to over estimate total tree needle biomass. In order to statistically compare the different trees, the data was normalized by setting the tree height at 100% and total tree needle biomass at 100% (see Appendix IV for the normalized graphs). It was decided

to split the canopy into crown tenths for added resolution. Data was combined by species (Figure 17, 18, 19), after which the estimated biomass was averaged and compared statistically with an F-test (Fig 20, 21, 22). Only comparison within a species was conducted. Data indicates that using importance sampling, branches collected between 30 and 50% of the total tree height up the stem will yield an excellent estimate of total needle biomass regardless of species. Figures 8 through 16 show estimates of 0 or near 0, and further examination of these points show that they are epicormic branches. It is obvious from the data that small epicormic branches under estimated biomass throughout the canopy and should be disregarded during sampling.

Both Douglas-fir and white fir show an even distribution of needle biomass per branch throughout the canopy (Fig. 23, 24). Mistletoe infection; however results in a highly altered branch biomass pattern (Fig. 25), in particular in the bottom third. Branches infected with mistletoe had high biomass levels (X = 884 g $\pm$ 64.9 [max = 5854 g]). Average biomass distribution per canopy tenth showed an even needle biomass distribution between 20 and 80 % of the tree height in white fir (Fig. 26). Douglas-fir showed a steady increase in biomass to the 40% strata, after which the needle biomass declined (Fig. 26). Mistletoe alters this pattern completely (Fig. 26), peak biomass was found in the 30, 50 and 60% strata. Mistletoe brooms contributed approximately 54.8% to the total canopy needle biomass. This means that the remaining 45.2% supply most of the photosynthates for tree maintenance and growth. Above 70% of the canopy height, growth of trees infected with mistletoe is greatly depressed. Conical crown shape found in the previous study is also seen here if we examine the trees by crown third (white fir - bottom : middle : top = 1.3 : 2.5 : 1; Douglas-fir = 3.1 : 4.6 : 1; Douglas-fir with DM = 5.6 : 11.4 : 1), which is similar to the study by Schmid and Morton (1981).

Estimation of current and last years' foliage was more complicated than expected. Branches at the top of the canopy which were young were relatively easy to sample; however, in the lower layers of the canopy, difficulties occurred. These difficulties included skipped

years, a very common property of Douglas-fir (Wilson, 1989), and the intricate branching in the lower part of the canopy, which makes it compilcated to sample. Previously, we had collected data on needle persistence on branches per canopy third for the three tree classes (Briede et al., 1991) and the same data was used to calculate relative percentage of needles per flush (Fig. 27). Little variation was seen among canopy thirds and percent current needles and last years' needles (Fig. 27). Values were lowest in the top of the canopy. This data; however, pertains to 1989, no data was available to 1990. Since this data is based on needle persistence, annual differences would probably not be profound. Flush growth during the year could have been incorporated in our calculations giving more precise results; however, we did not measure the flush growth during the 1990 season. Using the data on average biomass per branch (Fig. 23, 24, 25), we calculated the needle biomass per individual branch per canopy tenth (Fig. 18, 19, 30). Data followed closely the values for total biomass and little difference in needle percentage was seen per canopy third.

DISCUSSION

Data presented here indicate that the estimation of needle biomass can be relatively straight forward. First indications are that DIB seems to be a very good estimate of needle biomass, in particular when a quadratic equation is used ($R^2 = 0.98$). DBH also seems to be a fairly good estimate ($R^2 = 0.94$), while in white-fir current sapwood area of the past seven years also seems to be a very good estimate ($R^2 = 0.96$). All indications are that importance sampling (Valentine et al. 1984, Williams 1989) can be an excellent estimate, when restricted to the mid-crown area of 30 to 50% of the total tree height. On Douglas-fir in this research that would have been an average height between 3.8 and 6.4 m. With the proper climbing tools it would be possible to collect three or four sample branches from that height and calculate total tree biomass.

Comparing the different methods, we recommend DBH for a fast and relatively accurate biomass estimation technique. A quadratic equation seems to give the best results. The recommendation for this method is based on the ease in obtaining the data. Importance sampling and DIB are also good estimates of needle biomass; however, collection of the data is more complicated. A possible draw-back could be that DBH and DIB do not involve any actual sampling or harvesting of needles to verify estimates. Importance sampling does not necessarily need the sampling of branches and could suffice with branch diameter and bole diameter measurements. However, with importance sampling, needle biomass on individual branches could be determined by harvesting and weighing. This sampling of a branch could periodically assist in determining if foliage dynamics are similar among trees or among habitat types, by comparing branch length, branch diameter and needle biomass (Table 2); thus importance sampling could statistically be more precise. DBH and DIB do not allow for such verification.

Other indications from the data are that branch length and branch diameter are closely correlated. This indicates that factors which altere branch elongation also altere diameter growth. To determine this relationship only those branches were used that were taken to the laboratory for needle biomass sampling (n = 116, 69, 120 for Douglas-fir, Douglas-fir with dwarf mistletoe infection and white fir respectively, or 20% of the branches). Plans are to conduct similar analyses for all branches. Estimation of current and last years' needles is very complicated. There is a need to work out a method for easy determination in the field.

We have expanded our data on the effect of dwarf mistletoe on Douglas-fir growth, canopy architecture and needle biomass distribution. Together with the previous research the authors have conducted for the Forest Service, we have an extensive data set on this subject which allows for additional recalculations, analysis and publication.

PUBLICATIONS FROM THIS RESEARCH AND PREVIOUS WORK DONE FOR THE FOREST PEST MANAGEMENT AND METHODS APPLICATION GROUP

Previous research conducted by the authors on plant phenology and biomass include two journal articles, one artilce in symposium proceedings, one published abstract, and two presentations:

Jounal Articles:

Briedé, J.W., J.G. Mexal, and A.M. Lynch. In review. Shoot growth patterns and needle demography of Douglas-fir and white fir in Southern New Mexico. (Great Basin Nat.).

Briedé, J.W., J.G. Mexal, A.M. Lynch, and F.G. Hawksworth. In review. Douglas-fir (*Pseudotsuga menziessii*) growth and phenology as affected by dwarf mistletoe (*Arceuthobium douglasii*) infection in southern New Mexico. (Can. J. For. Res.).

Symposium proceedings:

Briedé, J.W., J.G. Mexal, A.M. Lynch, and F.G. Hawksworth. 1991. Shoot growth and development of Douglas-fir and white fir in New Mexico. In: D.M. Baumgartner and J. Lotan (Eds), Interior Douglas-fir Symposium: The species and its management. Spokane, WA. In Press.

Published Abstracts:

Briedé, J.W., J.G. Mexal, A.M. Lynch, and F.G. Hawksworth. 1990. Growth and development of Douglas-fir (*Pseudotsuga menziesii*) as affected by dwarf mistletoe (*Arceuthobium douglasii*). Plant Physiol. 93(sup):54.

Presentations:

Briedé, J.W. 1990. Shoot growth and development of Douglas-fir and white fir in New Mexico. Seminar Presented at the Departemental Seminar, Dept. of Agronomy and Horticulture, New Mexico State Univ., Las Cruces, NM.

Briedé, J.W., J.G. Mexal, A.M. Lynch, and F.G. Hawksworth. 1991. Douglas-fir dwarf mistletoe induced changes on phenology and growth of its host in the Lincoln National Forest of Southern New Mexico. Abstract and Presentation, Annual Meeting South-western Association of Naturalist, El Paso, TX.

We believe this research will possibly result in six articles in various journals or publications:

1. **Coniferous foliage biomass estimation: a review.** *Forest Science Monographs.*
2. **Needle biomass distribution in white-fir and Douglas-fir in the Lincoln National Forest.** *USDA, U.S. Forest Service Technical Report.* Reporting the raw data for each tree and some of the estimators.
3. **Use of importance sampling to estimate needle biomass in Douglas-fir and white fir.** *Forest Science.* A paper on the methodology of importance sampling.
4. **Sampling methods for needle biomass sampling in Douglas-fir and white fir in the Southwest.** *Western Journal of Applied Forestry.* A paper discussing all the methods used in this report.
5. **Dwarf mistletoe (*Arceuthobium douglasii* Engelm.) affects foliage biomass distribution and canopy architecture of *Pseudotsuga menziesii* (Mirb.) Franco as compared to *Abies concolor* (Gordon & Glendinning) Hoopes.** *Oecologia, Journal of Applied Ecology or Canadian Journal of Botany.* A

paper discussing the distribution of needle biomass and branches throughout the canopies.

6. **Dwarf mistletoe (*Arceuthobium douglasii* Engelm.) affects growth of *Pseudotsuga menziesii* (Mirb.) Franco.** *Southwestern Naturalist.* A summary of all our research on Douglas-fir dwarf mistletoe conducted for the U.S. Forest Service.

FUTURE WORK

The following studies are suggested:

1. Extend foliage biomass study to Carson and Santa Fe National Forests in Northern New Mexico, using importance sampling.
2. Cohort sampling and methods for current and last years biomass estimates.
3. A more frequent study of bud break and early growth in Douglas-fir and white fir in the Lincoln National Forest.
4. Develop 3-dimensional branch map of 1 tree of each species in conjunction with a stem map. This will allow us to determine the effect of interference by neighboring trees on branch length. Since length, diameter and foliage biomass are correlated, this information should improve the I.S. technique.
5. Extend importance sampling analysis to evaluate sapwood area and annual branch growth increment. As the pipe theory indicates this should improve the predictability of the model.
6. Reanalyze Brown's data in light of developments from this project.
7. Foliage annual ring analysis.

PERSONNEL REQUIREMENT

Publication:

1. Needle biomass distribution	P.I.[1]	= 4 wks
	Tech.	= 2 wks
2. Importance sampling	P.I.	= 4 wks
	Tech.	= 1 wk
3. Sampling methods	P.I.	= 4 wks
4. Dwarf mistletoe affects foliage ...	P.I.	= 6 wks
	Tech.	= 3 wks
5. Foliage literature review	P.I.	= 8 wks
	Tech.	= 4 wks
6. Dwarf mistletoe affects growth ...	P.I.	= 4 wks
	Tech.	= 1 wk

Research

1. Bud break phenology	P.I.	=12 wks
	Tech.	= 8 wks
2. Foliage biomass (Northern NM)	P.I.	=12 wks
	Tech.	=32 wks
3. 3-D maps	P.I.	= 3 wks
4. Pipe theory (sapwood)	P.I.	= 6 wks
	Tech.	= 8 wks
5. Brown's data	P.I.	= 8 wks
	Tech.	= 8 wks
6. Foliage annual rings	P.I.	= 3 wks
	Tech.	= 6 wks
TOTAL	**P.I.**	**=74 wks**
	Tech.	**=73 wks**

The time table above assumes each project would be conducted separately. Obviously, considerable efficiency is gained by budgeting several projects at the same time. Although it is realistic to expect that a full time P.I. would need about 6 months to finish manuscript preparation and one year to a year and three months for the entire plan. Furthermore, whenever possible, student labor would be used to reduce cost.

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[1] P.I. is J.W. Briedé. The technician needed for the publications is for additional work with data entry, current sapwood analysis and library work.

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Briedé, J.W., J.G. Mexal, A.M. Lynch, and F.G. Hawksworth. 1991. Douglas-fir dwarf mistletoe induced changes on phenology and growth of its host in the Lincoln National Forest of Southern New Mexico. Abstract and Presentation, Annual Meeting South-western Association of Naturalist, El Paso, TX.

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Table 1. Stand and sample tree characteristics. Number corresponds with the order of harvesting.

TREE[a]	HEIGHT (m)	DBH (cm)	CROWN LENGTH (m)	AGE (yr)	TREES/ha (no.)	BA (m^2/ha)
1. Douglas-fir 1	9.25	20.5	7.60	87	1401	63.28
2. White fir 1	14.50	18.2	12.85	60	637	12.61
3. Douglas-fir 2	20.10	36.7	17.10	76	637	31.32
4. Douglas-fir 3	10.60	18.7	9.29	49	255	5.86
5. Douglas-fir 4	12.30	25.3	10.55	57	382	13.88
6. White fir 2	13.80	35.6	12.95	74	637	31.07
7. White fir 3	11.55	23.2	10.45	64	1019	46.22
8. Douglas-fir+m 1	15.86	41.3	13.75	78	255	30.43
9. White fir 4	14.00	22.9	13.10	60	891	26.61
10. Douglas-fir+m 2	10.60	15.5	9.75	66	382	8.14
11. White fir 5	7.10	11.2	5.40	54	637	14.64
12. Douglas-fir+m 3	11.90	20.8	8.75	73	637	24.83
13. Douglas-fir 5	11.25	16.5	11.10	37	764	17.06
14. White fir 6	26.40	48.6	25.25	78	255	39.34
15. Douglas-fir+m 4	9.30	19.0	8.80	63	382	6.75
16. Douglas-fir 6	12.50	23.0	11.65	63	382	23.55
17. Douglas-fir+m 5	6.85	15.5	5.80	84	509	41.13
18. Douglas-fir+m 6	10.50	19.5	7.85	84	891	27.63

[a]+m=mistletoe infected tree

Table 2. Regression models relating branch length (BL), branch diameter (BD) and needle biomass.

	R^2	p-value[a]
DOUGLAS-FIR WITHOUT DWARF MISTLETOE		
BD X BL	.73	.0001
BD X Needle biomass	.56	.0001
BD X BL X Needle biomass	.62	.0001 (n.s. impr)
DOUGLAS-FIR WITH DWARF MISTLETOE		
BD X BL	.65	.0001
BD X Needle biomass	.47	.0001
BD X BL X Needle biomass	.47	.0001 (n.s. impr)
WHITE FIR		
BD X BL	.59	.0001
BD X Needle biomass)	.68	.0001
BD X BL X Needle biomass	.69	.0001 (n.s. impr)

[a] n.s. impr = no significant improvement from aditional variable

Table 3. Tree biomass estimated using branch diameter and using Mouer's equations. Number corresponds with the order of harvesting and are the same as in Table 1.

TREE[a]	HEIGHT (m)	DBH (cm)	CROWN LENGTH (m)	NEEDLE BIOMASS BRANCH (kg)	NEEDLE BIOMASS MOUER (kg)
1. Douglas-fir 1	9.25	20.5	7.60	17.40	12.73 (- 26.8%)
3. Douglas-fir 2	20.10	36.7	17.10	39.55	75.44 (+ 90.7%)
4. Douglas-fir 3	10.60	18.7	9.29	16.20	24.38 (+ 50.5%)
5. Douglas-fir 4	12.30	25.3	10.55	19.36	38.30 (+ 97.9%)
13. Douglas-fir 5	11.25	16.5	11.10	11.09	14.81 (+ 12.1%)
16. Douglas-fir 6	12.50	23.0	11.65	18.94	24.91 (+ 31.5%)
8. Douglas-fir+m 1	15.86	41.3	13.75	57.94	91.50 (+ 85.5%)
10. Douglas-fir+m 2	10.60	15.5	9.75	13.31	13.04 (+ 85.5%)
12. Douglas-fir+m 3	11.90	20.8	8.75	15.26	17.11 (+ 9.7%)
15. Douglas-fir+m 4	9.30	19.0	8.80	10.05	26.45 (+163.3%)
17. Douglas-fir+m 5	6.85	15.5	5.80	7.99	6.81 (- 14.8%)
18. Douglas-fir+m 6	10.50	19.5	7.85	16.58	13.26 (- 20.1%)
2. White fir 1	14.50	18.2	12.85	16.73	23.75 (+ 42.0%)
6. White fir 2	13.80	35.6	12.95	33.55	119.91 (+257.4%)
7. White fir 3	11.55	23.2	10.45	19.90	38.43 (+ 93.1%)
9. White fir 4	14.00	22.9	13.10	22.15	41.09 (+ 57.9%)
11. White fir 5	7.10	11.2	5.40	5.38	5.90 (- 2.0%)
14. White fir 6	26.40	48.6	25.25	103.58	173.39 (+ 67.4%)

[a]+m=mistletoe infected tree

Table 4. Foliage biomass estimation technique comparison for the three tree classes (DF = Douglas-fir, dm = dwarf mistletoe and wf = white fir).

COMPARISON METHOD METHOD	TYPE	R^2	error estimate	Equation Coefficients Slope	Intercept
DBH	DF -dm	.96 ***	+ 6.5%	1337.2	-10934.6
	DF +dm	.97 ****	- 0.3%	1895.9	-21393.8
	WF	.86 **	+ 2.1%	2454.7	-31788.4
DBH (+ winter trees)	DF -dm	.89 ****	+ 1.8%	1332.0	- 9713.3
	DF +dm	.96 ****	+ 1.4%	1851.2	-20968.1
	WF	.85 ***	- 7.4%	2304.9	-25704.1
	COMBINATION OF ALL TREE TYPES				
	linear	.85 ****		2046.2	-23497.2
	quardratic	.94 ****		$(Y = 72.06\ X^2 - 2156.03\ X + 29211.16)$	
DIB (at ground level)	DF -dm	.99 ****		1563.0	-18157.3
	DF +dm	.94 ***		1804.4	-19990.1
	WF	.92 **		2412.3	-39418.4
	COMBINATION OF ALL TREE TYPES				
	linear	.90 ****		2096.0	-29216.9
	quardratic	.98 ****		$(Y = 50.8\ X^2 - 1230.53\ X + 17312.29)$	
1st year's growth incr.	DF -dm	.40 §		645.7	7184.6
	DF +dm	.83 *		1404.6	-2285.6
	WF	.88 **		662.5	-164.2
5th-7th year's growth incr.	DF -dm	.40 §		241.6	-3407.4
	DF +dm	.75 *		400.4	-10098.4
	WF	.96 ****		211.4	-15172.3
Height	DF -dm	.84 **		2765.7	-13918.3
	DF +dm	.80 *		5617.2	-40196.2
	WF	.91 **		5285.7	-43401.8
MULTIPLE REGRESSION	DF -dm	.98 **	*(DBH+5/7y)*		
	DF +dm	--			
	WF	--			
	COMBINATION OF ALL TREE TYPE				
		.93 ****	*(DBH+5/7y)*		
		.89 ****	*(DBH+1y)*		
		.90 ****	*(DBH+Height)*		
Moeur's method	DF -dm		+46.2%		
	DF +dm		+32.7%		
	WF		+92.5%		

§ sign. at p<.20
* sign. at p<.05
** sign. at p<.01
*** sign. at p<.001
**** sign. at p<.0001

LIST OF FIGURES.

Figure 1. Relationship between DBH and needle biomass, data for the fall period only.

Figure 2. Relationship between DIB at ground level and needle biomass, data for the fall period only.

Figure 3. Relationship between DIB at ground level and needle biomass, data for the fall period only. Data for the three tree classes are pooled. Solid line is the linear relationship, while the dashed line depicts the quadratic.

Figure 4. Relationship between DBH and needle biomass, data for the fall and spring period, which added two Douglas-fir trees, one Douglas-fir with mistletoe and two white fir tees to the points shown in figure 1.

Figure 5. Relationship between DBH and needle biomass, data for the fall and spring period. Data for the three tree classes are pooled. Solid line is the linear relationship, while the dashed line depicts the quadratic.

Figure 6. Relationship between needle biomass an the area of that year's growth increment, data for fall period only.

Figure 7. Relationship between needle biomass an the area of the growth increment of the past five years (Douglas-fir) or seven years (white fir). Data for fall period only.

Figure 8. Raw data for the fall period, df=Douglas-fir, number correlate with the same tree number as table 1. Dashed line is the actual biomass, points give the biomass estimated by individual branches using the importance sampling technique.

Figure 9. Raw data for the fall period, df=Douglas-fir, number correlate with the same tree number as table 1. Dashed line is the actual biomass, points give the biomass estimated by individual branches using the importance sampling technique.

Figure 10. Raw data for the fall period, df=Douglas-fir, number correlate with the same tree number as table 1. Dashed line is the actual biomass, points give the biomass estimated by individual branches using the importance sampling technique.

Figure 11 Raw data for the fall period (df 8 +m=Douglas-fir no. 8 +dwarf mistletoe), number correlate with the same tree number as table 1. Dashed line is the actual biomass, points give the biomass estimated by individual branches using the importance sampling technique.

Figure 12. Raw data for the fall period (df 12 +m=Douglas-fir no. 12 +dwarf mistletoe), number correlate with the same tree number as table 1. Dashed line is the actual biomass, points give the biomass estimated by individual branches using the importance sampling technique.

Figure 13. Raw data for the fall period (df 17 +m=Douglas-fir no. 17 +dwarf mistletoe), number correlate with the same tree number as table 1. Dashed line is the actual biomass, points give the biomass estimated by individual branches using the importance sampling technique.

Figure 14. Raw data for the fall period (wf=white fir), number correlate with the same tree number as table 1. Dashed line is the actual biomass, points give the biomass estimated by individual branches using the importance sampling technique.

Figure 15. Raw data for the fall period (wf=white fir), number correlate with the same tree number as table 1. Dashed line is the actual biomass, points give the biomass estimated by individual branches using the importance sampling technique.

Figure 16. Raw data for the fall period (wf=white fir), number correlate with the same tree number as table 1. Dashed line is the actual biomass, points give the biomass estimated by individual branches using the importance sampling technique.

Figure 17. Pooled data for all Douglas-fir trees normalized by height and weight.

Figure 18. Pooled data for all Douglas-fir trees with dwarf mistletoe infections, normalized by height and weight.

Figure 19. Pooled data for all white fir trees normalized by height and weight.

Figure 20. Mean predicted (solid line) and actual normalized biomass (dashed line) for the three tree types. Bars are standard error bars and when not shown the error falls within the mark. Points within tree type accompanied by the same letter are not significantly different using LSD at the $p<.05$ level (note log scale).

Figure 21. Mean predicted (solid line) and actual normalized biomass (dashed line) for the three tree types. Shaded area show the 90% confidence interval of the mean (note log scale).

Figure 21. Comparison of the mean predicted and actual normalized biomass (dashed line) for the three tree types. The highest point for Douglas fir was omitted in order to get a better resolution.

Figure 23. Average needle biomass per branch by canopy tenth for Douglas-fir.

Figure 24. Average needle biomass per branch by canopy tenth for white fir.

Figure 25. Average needle biomass per branch by canopy tenth for Douglas-fir with dwarf mistletoe infection.

Figure 26. Average total needle biomass for the three tree types, normalized by canopy tenth.

Figure 27. Average contribution of needle age to the total bioamss per branch per conopy layer.

Figure 28. Average needle biomass per needle age class per branch by canopy tenth for Douglas-fir.

Figure 29. Average needle biomass per needle age class per branch by canopy tenth for Douglas-fir with dwarf mistletoe infection.

Figure 30. Average needle biomass per needle age class per branch by canopy tenth for white fir.

APPENDIX I. Schematic lay-out of the research site.

APPENDIX IV. Normalized data for the individual trees (see Fig. 8 through Fig. 16).

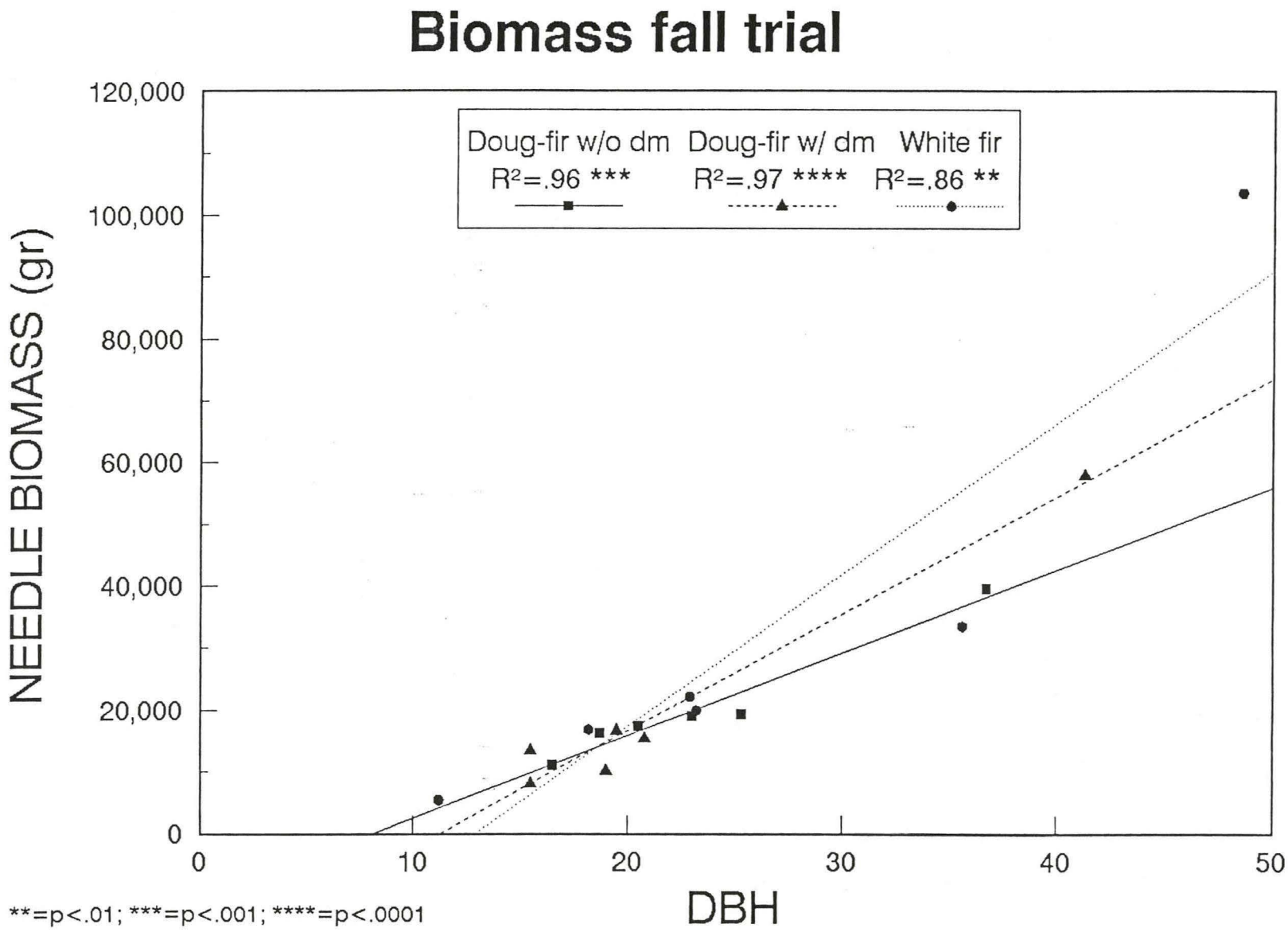
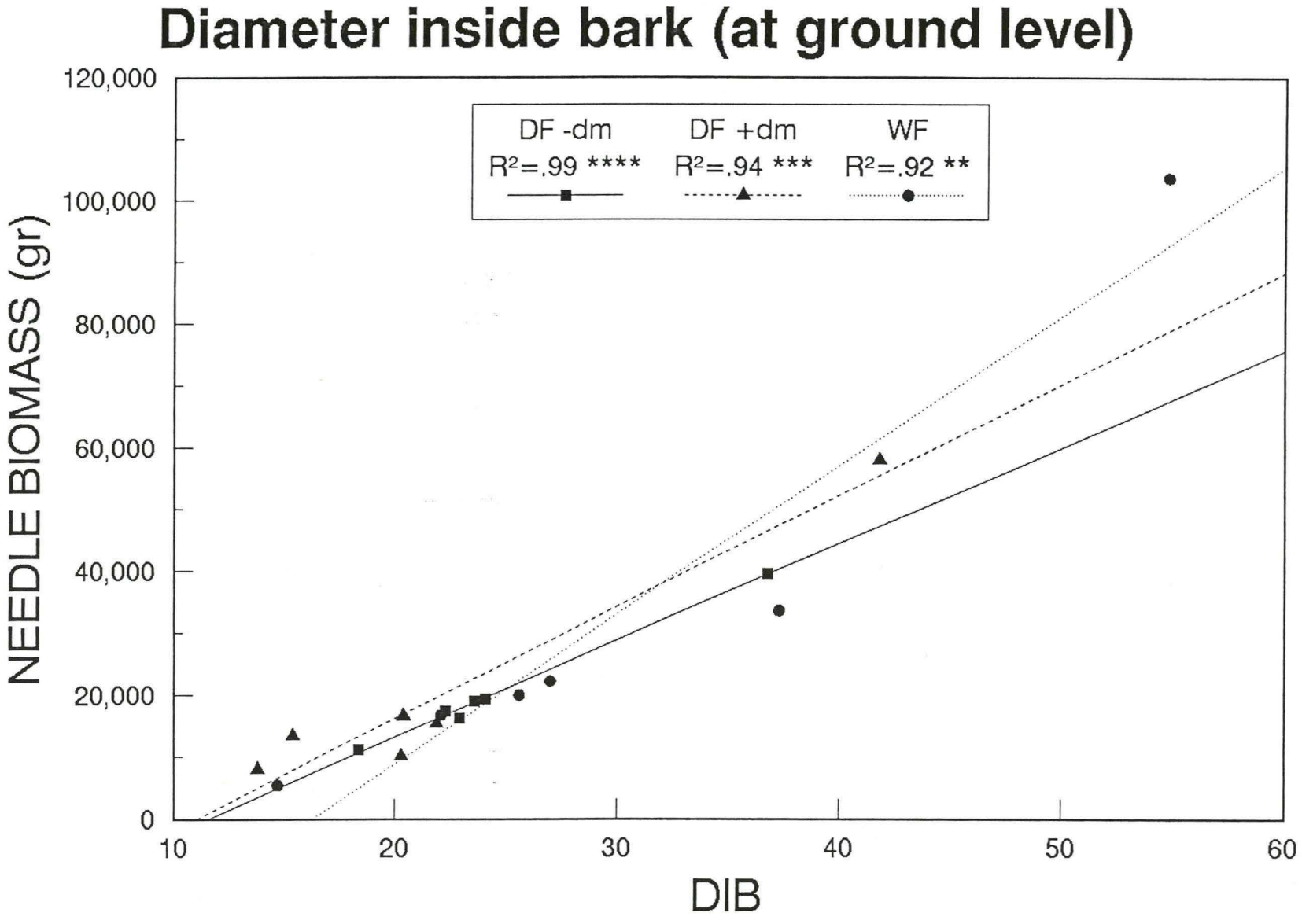
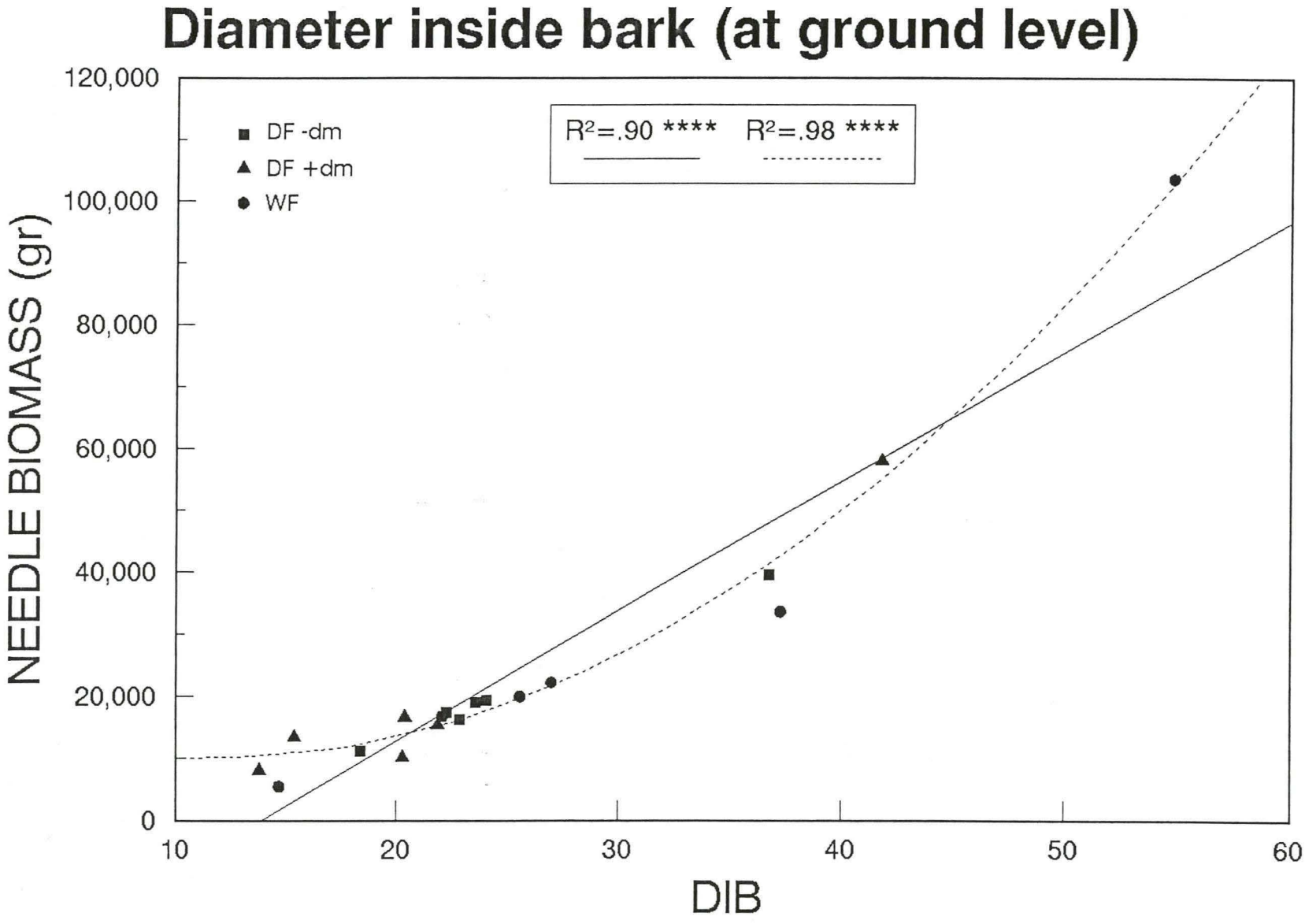

Biomass fall trial
Doug-fir w/o dm
R²=.96 ***
Doug-fir w/ dm
R²=.97 ****
White fir
R²=.86 **
NEEDLE BIOMASS (gr)
120,000
100,000
80,000
60,000
40,000
20,000
0
0
10
20
30
40
50
DBH
**=p<.01; ***=p<.001; ****=p<.0001

FIGURE 1.



**=p<.01; ***=p<.001; ****=p<.0001

Figure 2.



****=p<.0001

FIGURE 3.

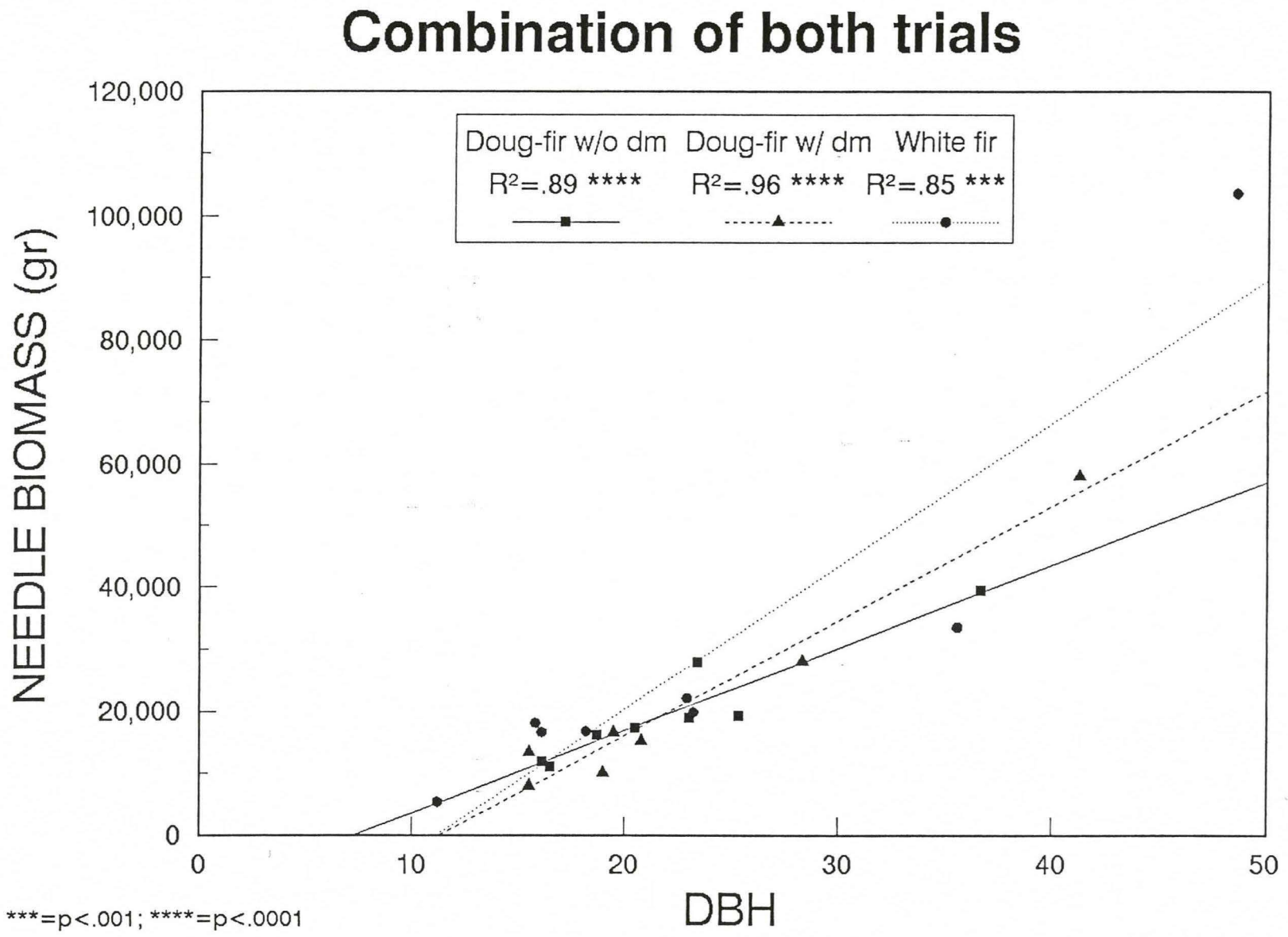
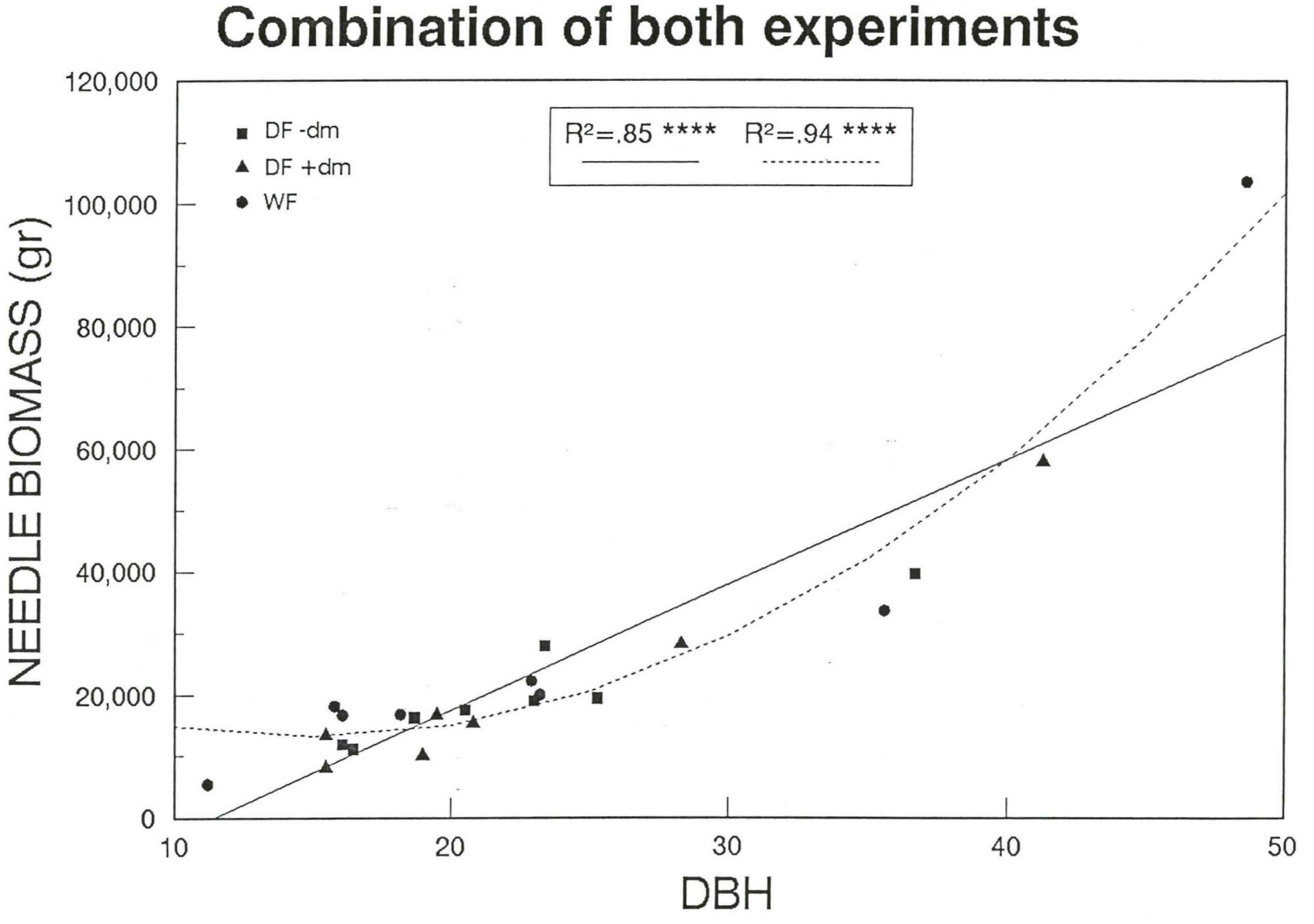
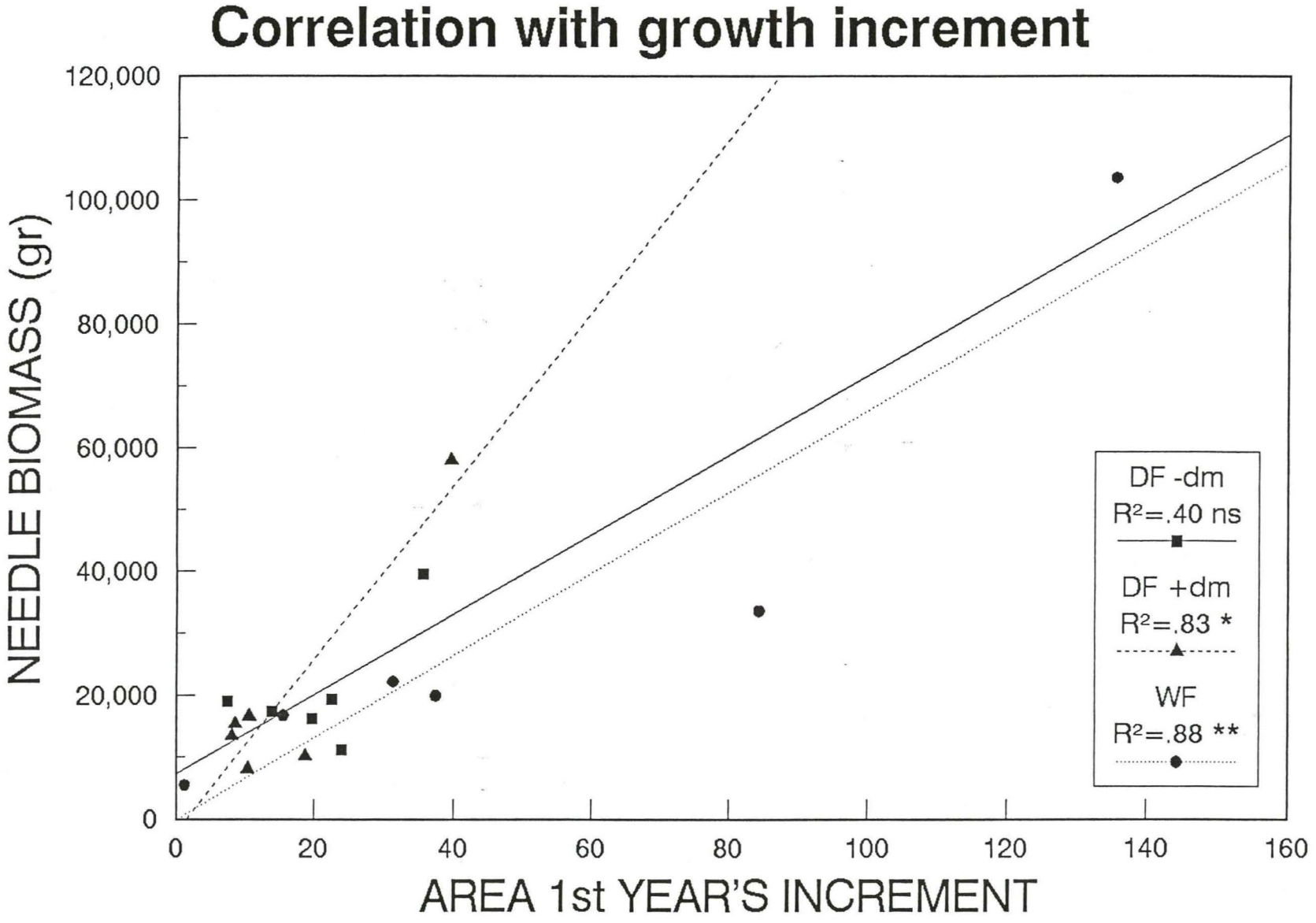

Combination of both trials
Doug-fir w/o dm
R²=.89 ****
Doug-fir w/ dm
R²=.96 ****
White fir
R²=.85 ***
NEEDLE BIOMASS (gr)
120,000
100,000
80,000
60,000
40,000
20,000
0
0
10
20
30
40
50
DBH
***=p<.001; ****=p<.0001

FIGURE 4.



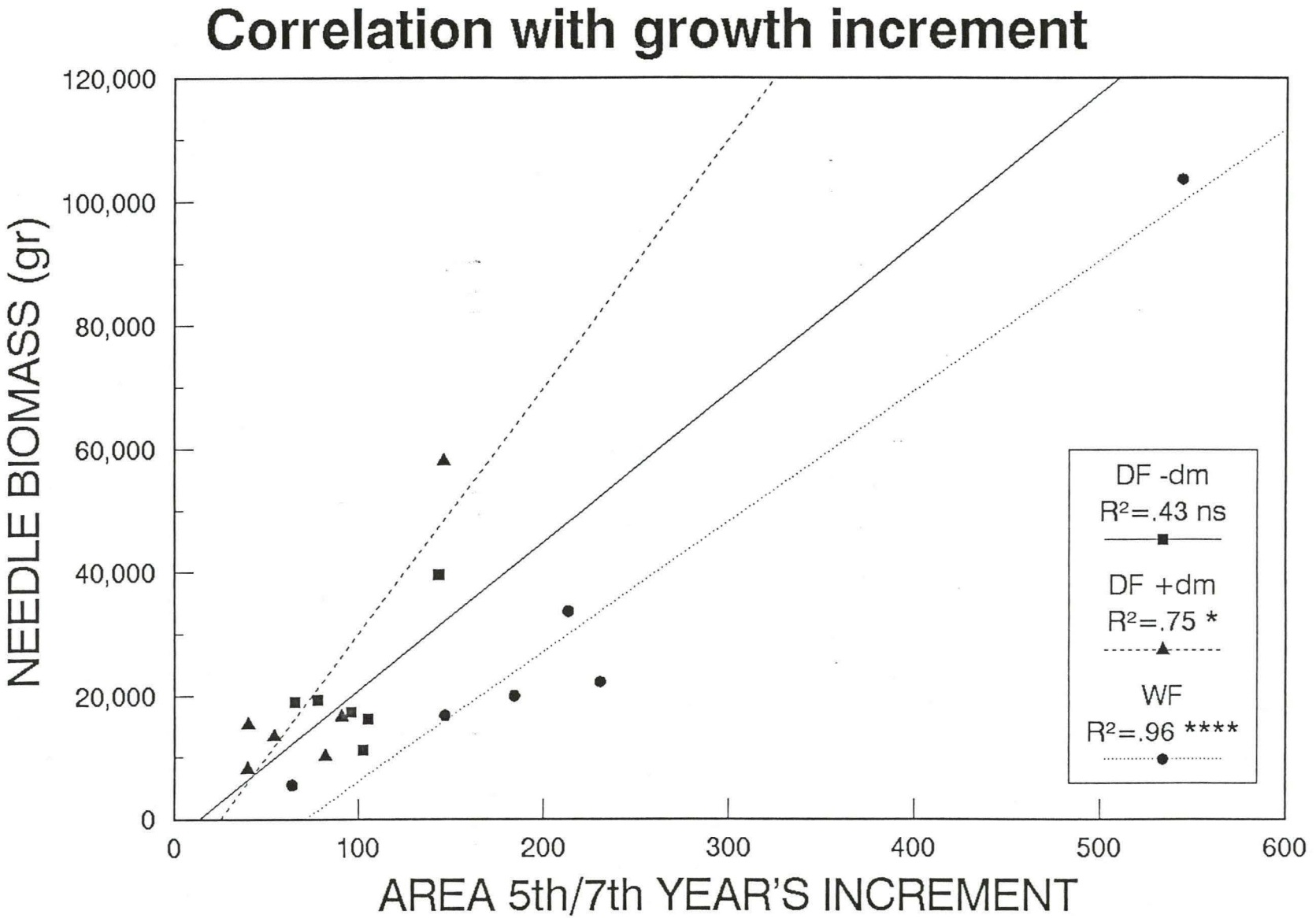
****=p<.0001

FIGURE 5.



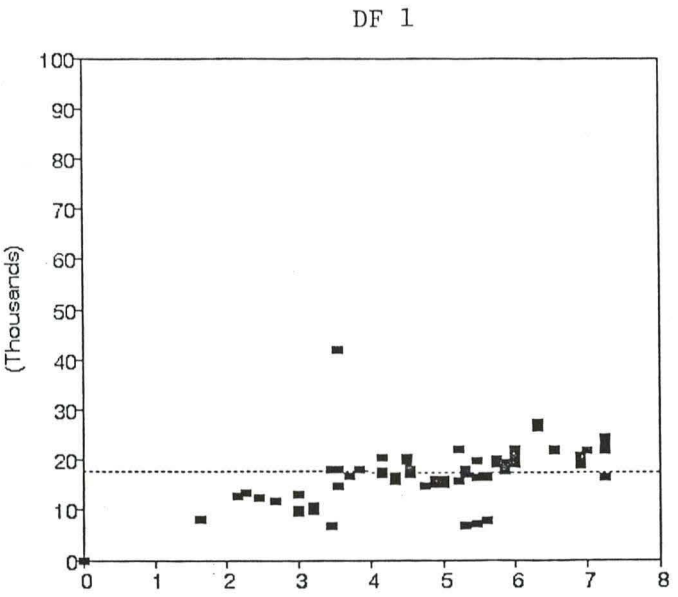
ns=not sign.; *=p<.05; **=p<.01

FIGURE 6.



ns=not sign.; *=p<.05; ****=p<.0001

FIGURE 7.


DF 1
(Thousands)
100
90
80
70
60
50
40
30
20
10
0
0
1
2
3
4
5
6
7
8

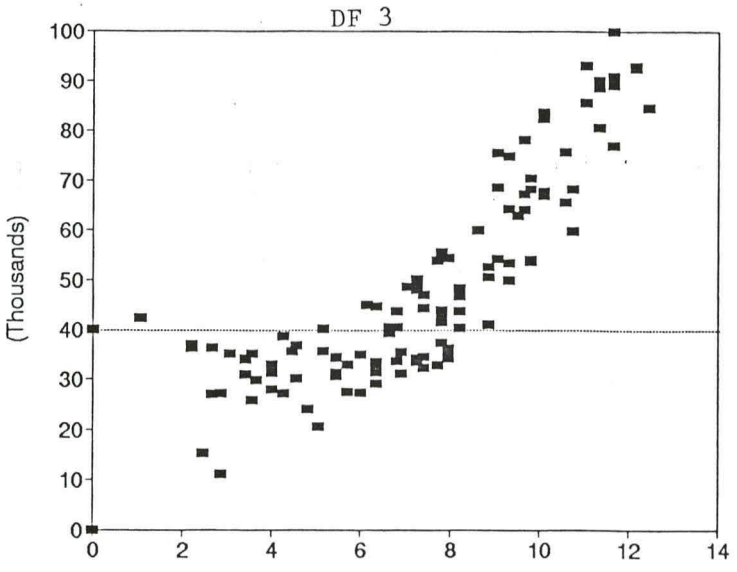
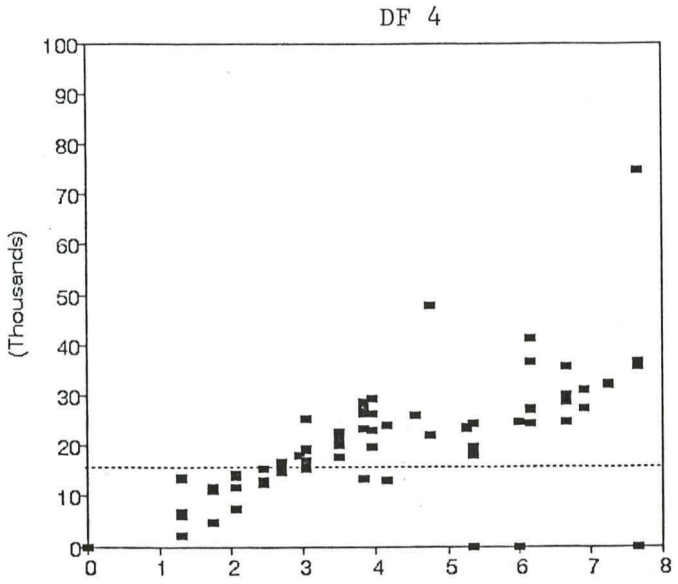

DF 3
(Thousands)
100
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14

FIGURE 8.



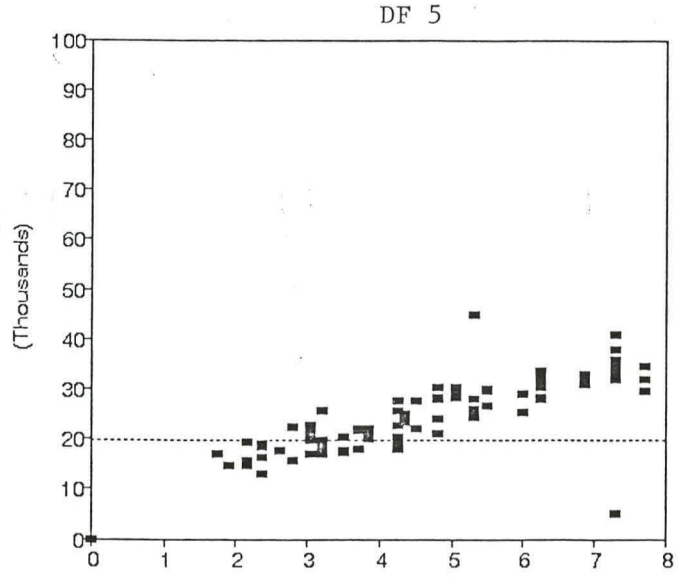
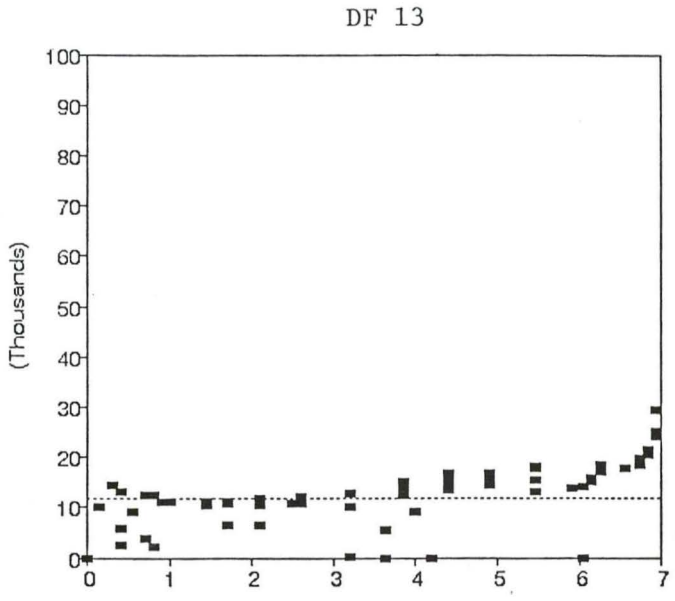


FIGURE 9.

LIBRARY COPY
ROCKY MTN. FOREST & RANGE
EXPERIMENT STATION

df 13



df, 6

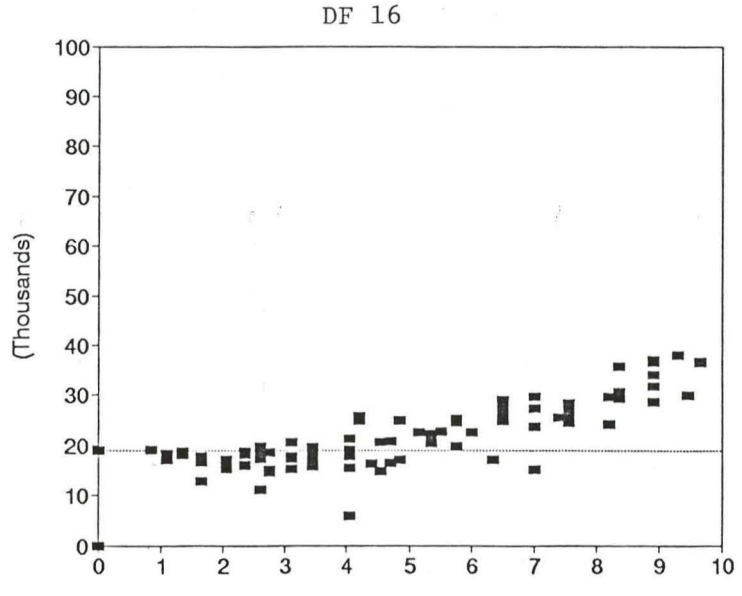
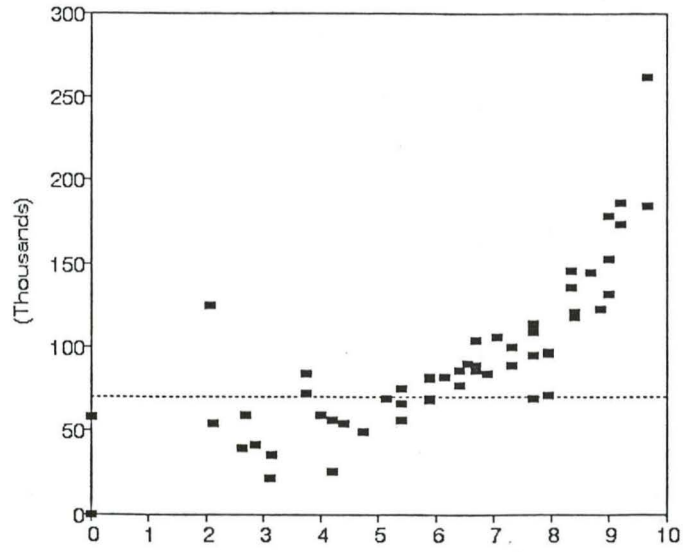


FIGURE 10.

DF 8 +M



DF 10 +M

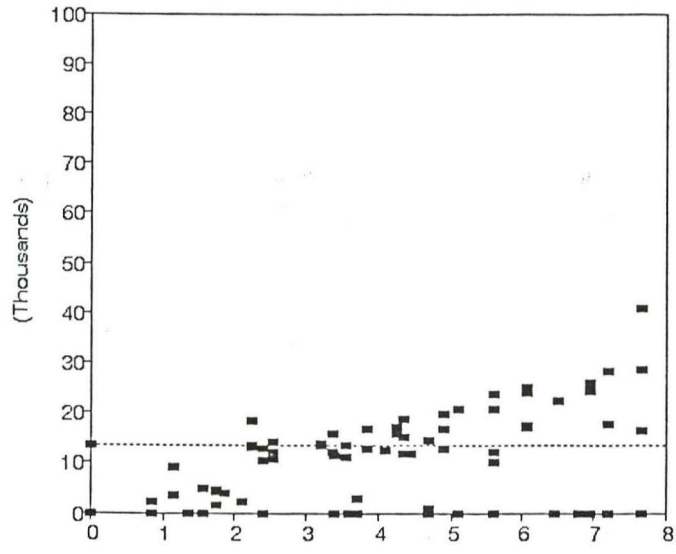
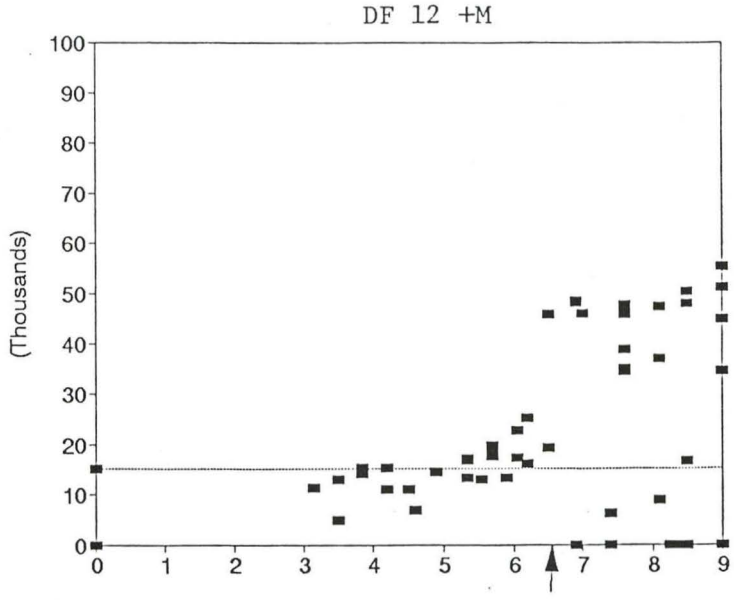


FIGURE 11.


DF 12 +M
(Thousands)
100
90
80
70
60
50
40
30
20
10
0
0 1 2 3 4 5 6 7 8 9

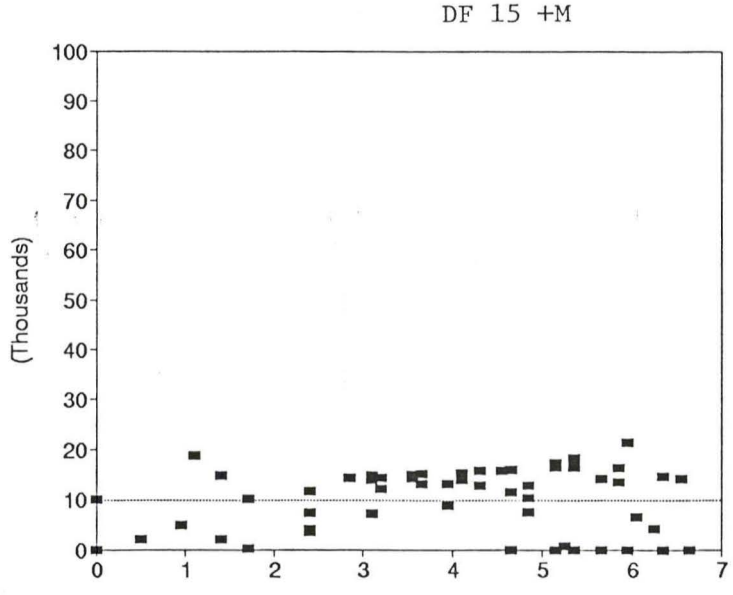
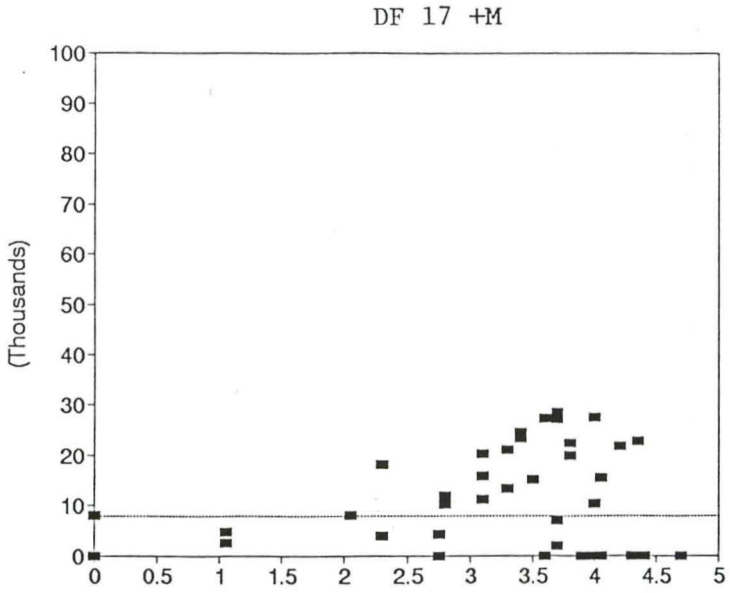

DF 15 +M
(Thousands)
100
90
80
70
60
50
40
30
20
10
0
0 1 2 3 4 5 6 7

FIGURE 12.

df 17 +M



df 18 +M

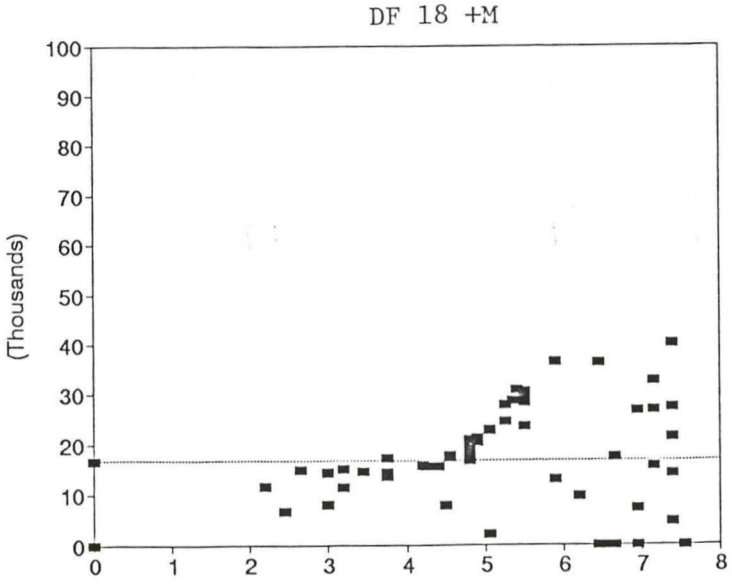
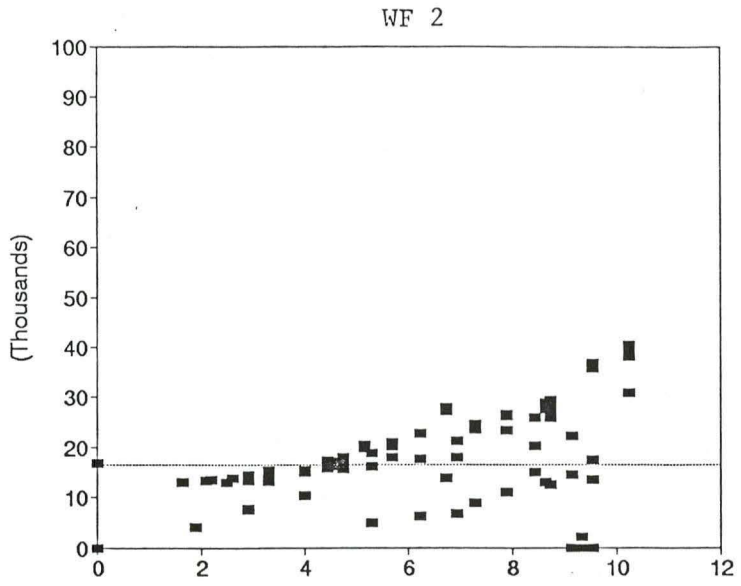


FIGURE 13.


WF 2
(Thousands)
100
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12

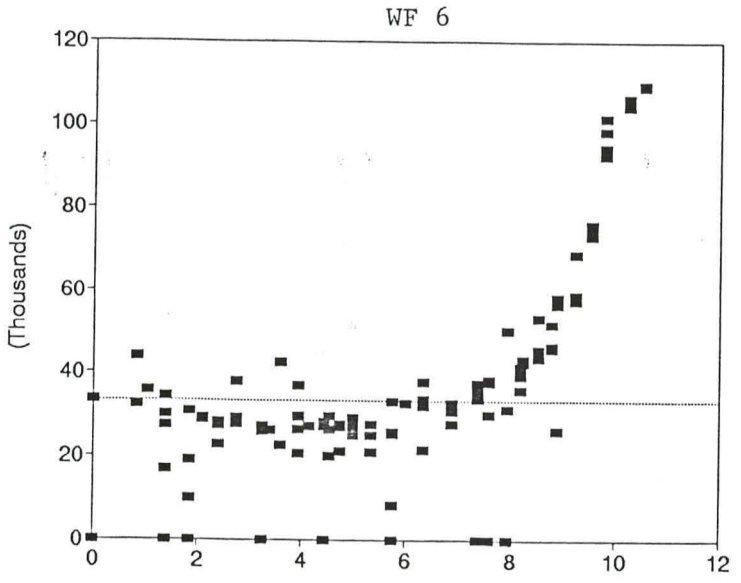
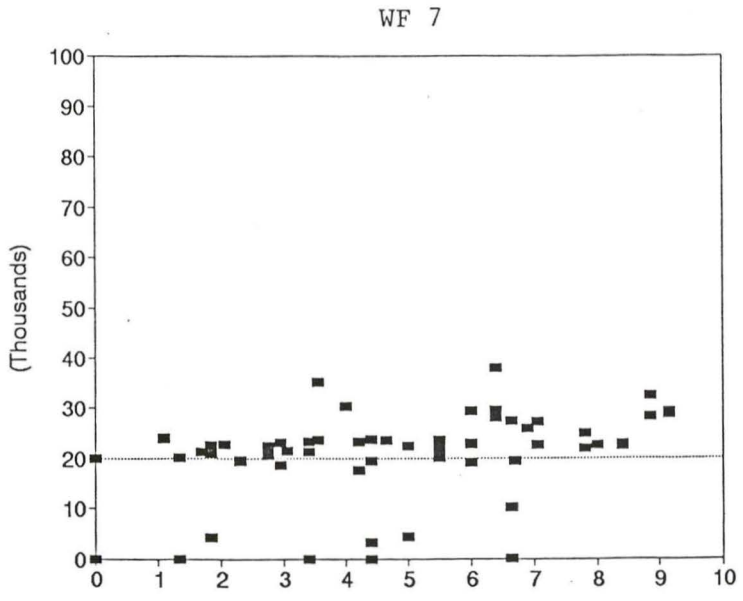

WF 6
(Thousands)
120
100
80
60
40
20
0
0
2
4
6
8
10
12

FIGURE 14.


WF 7
(Thousands)
100
90
80
70
60
50
40
30
20
10
0
0 1 2 3 4 5 6 7 8 9 10

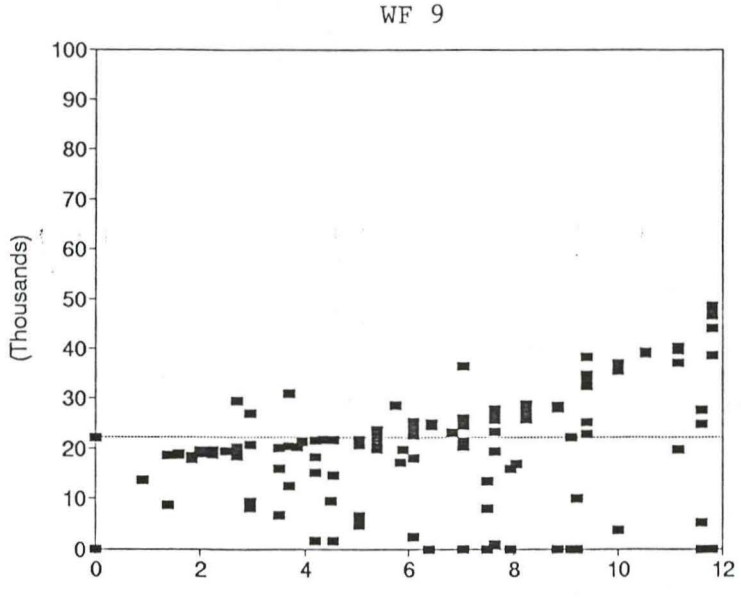
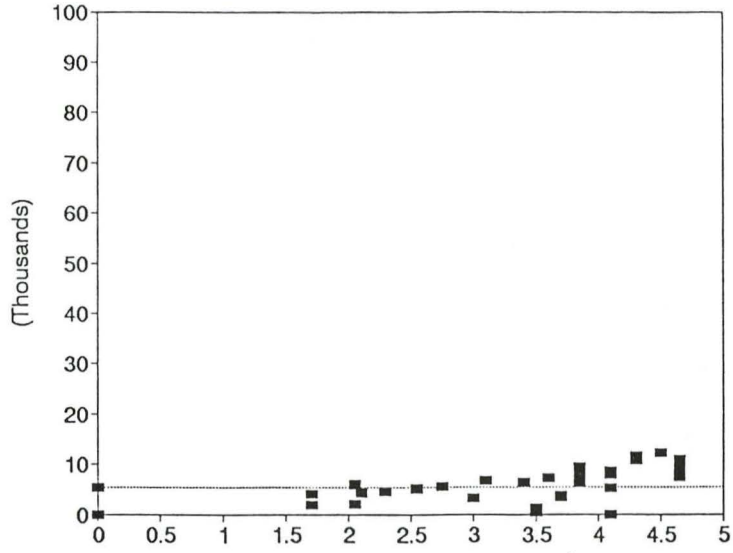
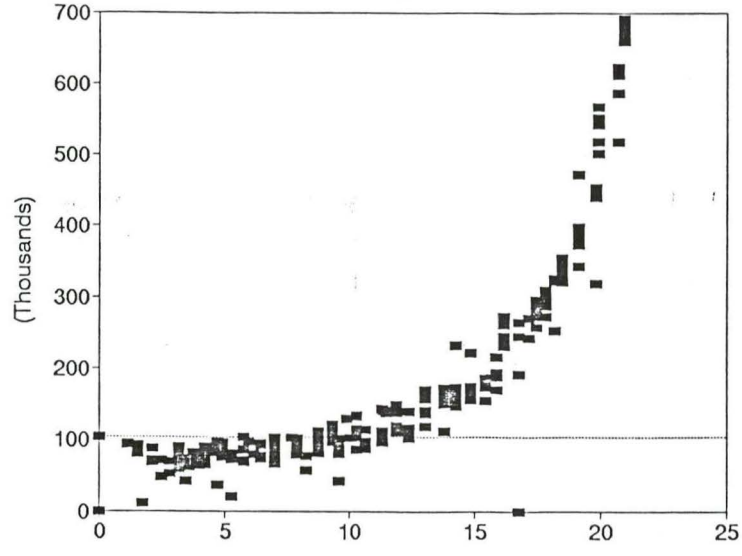

WF 9
(Thousands)
100
90
80
70
60
50
40
30
20
10
0
0 2 4 6 8 10 12

FIGURE 15.

WF 11


100
90
80
70
60
50
40
30
20
10
0
(Thousands)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

WF 14


700
600
500
400
300
200
100
0
(Thousands)
0
5
10
15
20
25

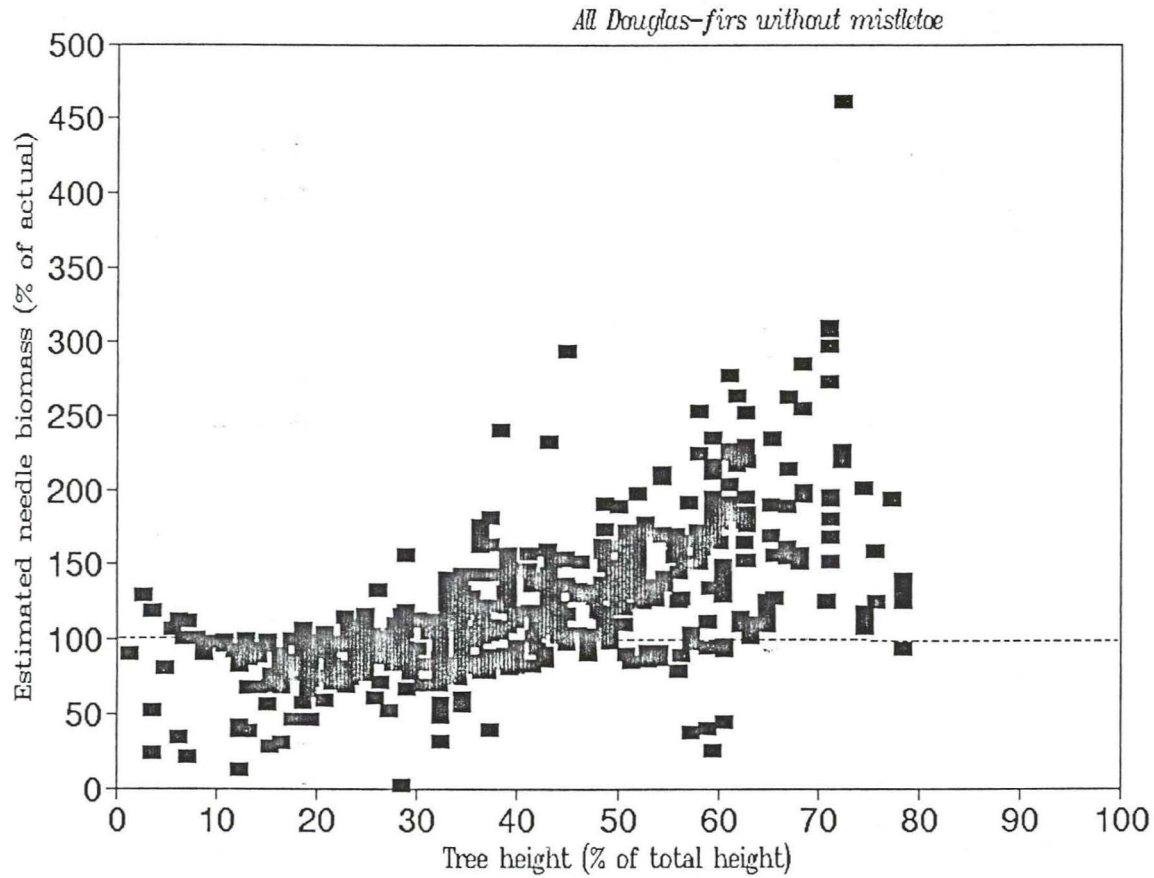

All Douglas-firs without mistletoe
Estimated needle biomass (% of actual)
500
450
400
350
300
250
200
150
100
50
0
0
10
20
30
40
50
60
70
80
90
100
Tree height (% of total height)

FIGURE 17.

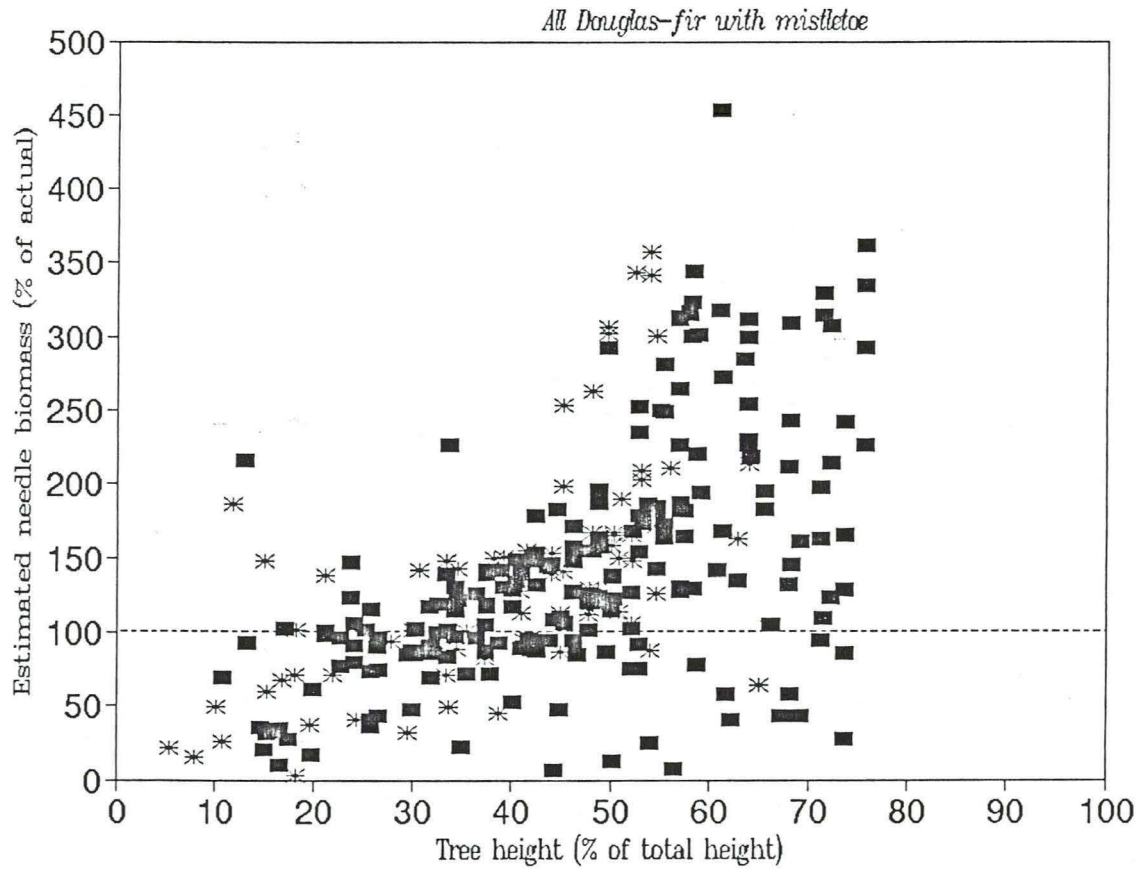

All Douglas-fir with mistletoe
Estimated needle biomass (% of actual)
500
450
400
350
300
250
200
150
100
50
0
0
10
20
30
40
50
60
70
80
90
100
Tree height (% of total height)

FIGURE 18.

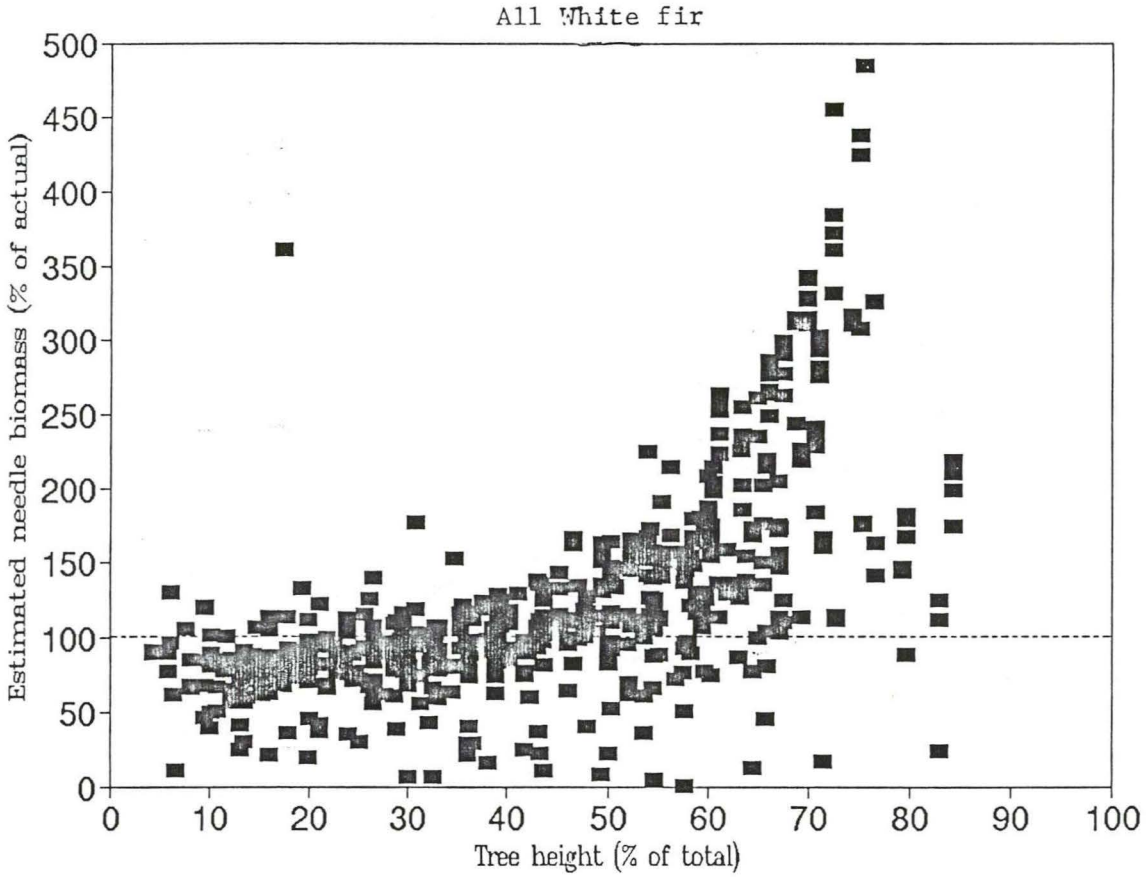

All White fir
Estimated needle biomass (% of actual)
500
450
400
350
300
250
200
150
100
50
0
0
10
20
30
40
50
60
70
80
90
100
Tree height (% of total)

FIGURE 19.

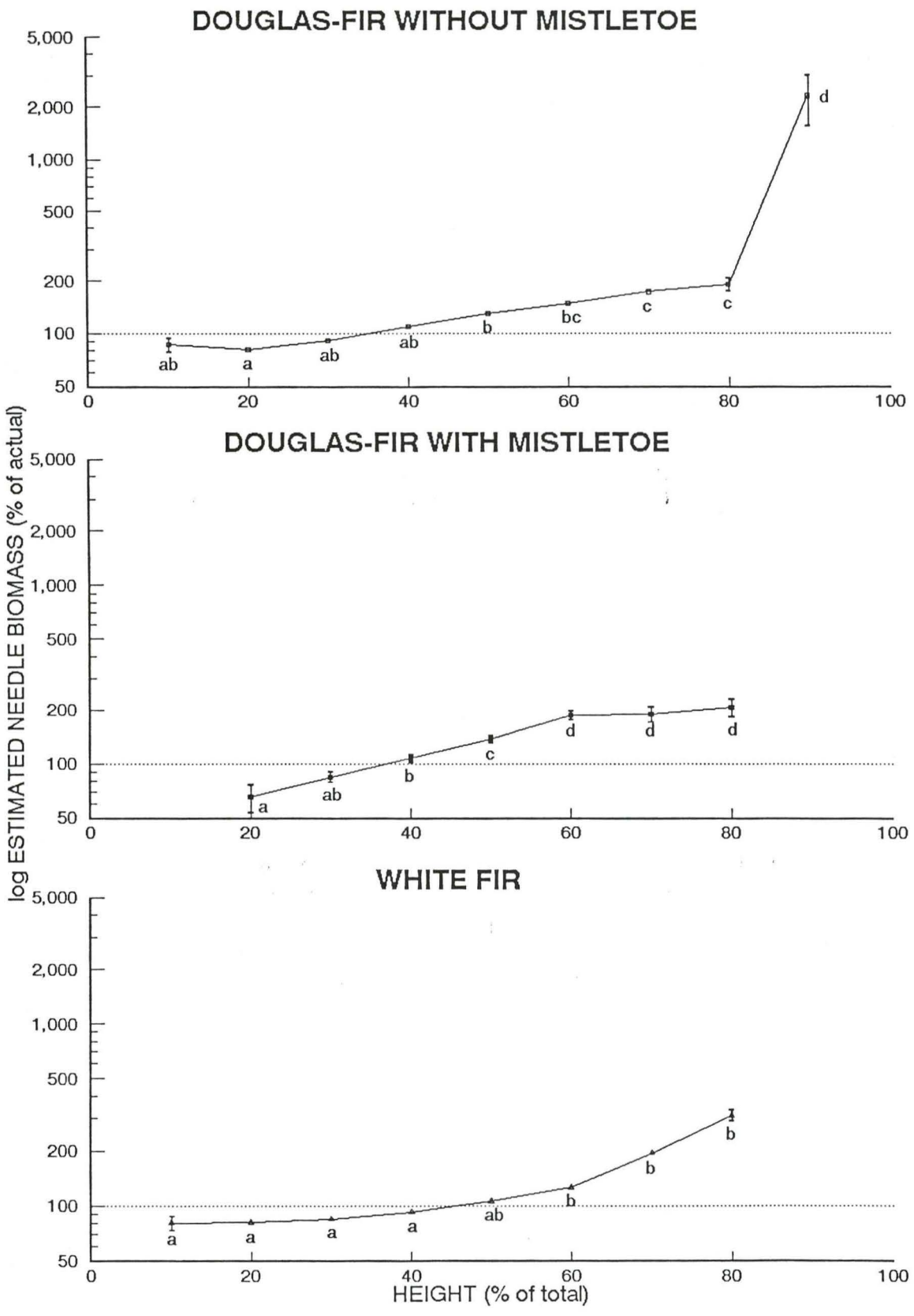

DOUGLAS-FIR WITHOUT MISTLETOE
DOUGLAS-FIR WITH MISTLETOE
WHITE FIR
log ESTIMATED NEEDLE BIOMASS (% of actual)
HEIGHT (% of total)
5,000
2,000
1,000
500
200
100
50
0
20
40
60
80
100
ab
a
ab
ab
b
bc
c
c
d
a
ab
b
c
d
d
d
a
a
a
a
ab
b
b
b

FIGURE 20.

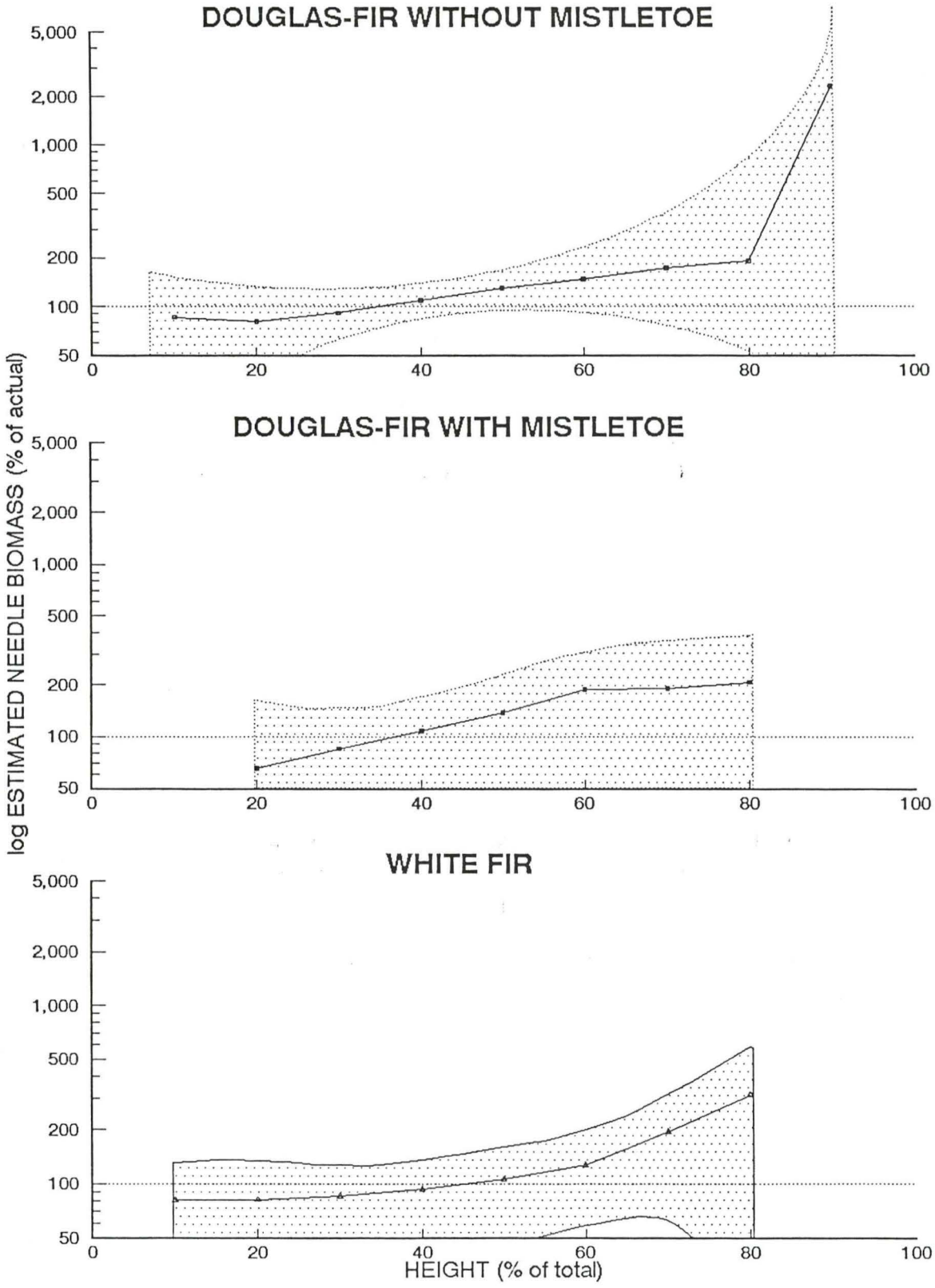

DOUGLAS-FIR WITHOUT MISTLETOE
DOUGLAS-FIR WITH MISTLETOE
WHITE FIR
log ESTIMATED NEEDLE BIOMASS (% of actual)
5,000
2,000
1,000
500
200
100
50
0
20
40
60
80
100
HEIGHT (% of total)

FIGURE 21.

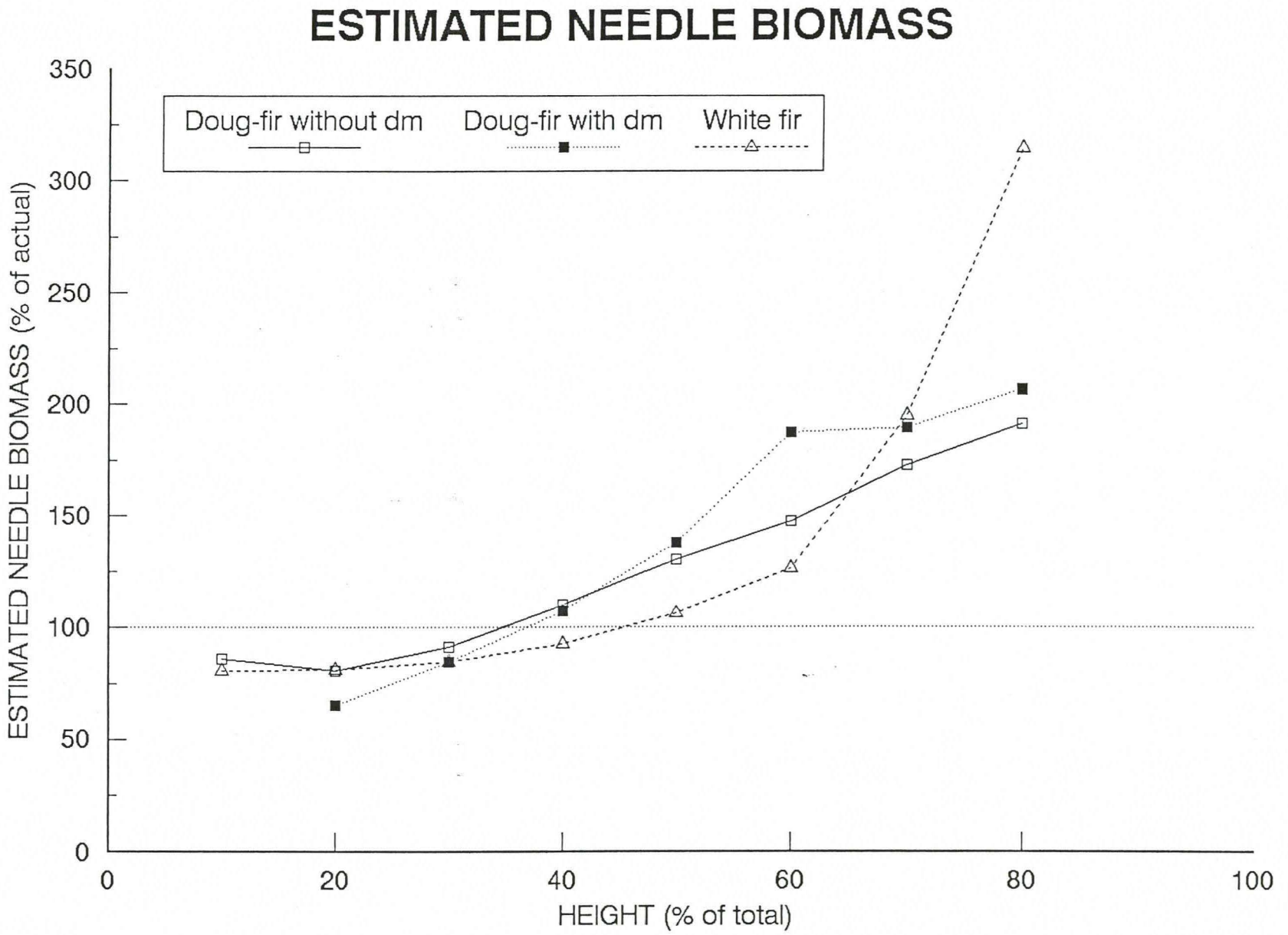

ESTIMATED NEEDLE BIOMASS
Doug-fir without dm
Doug-fir with dm
White fir
ESTIMATED NEEDLE BIOMASS (% of actual)
350
300
250
200
150
100
50
0
0
20
40
60
80
100
HEIGHT (% of total)

FIGURE 22.

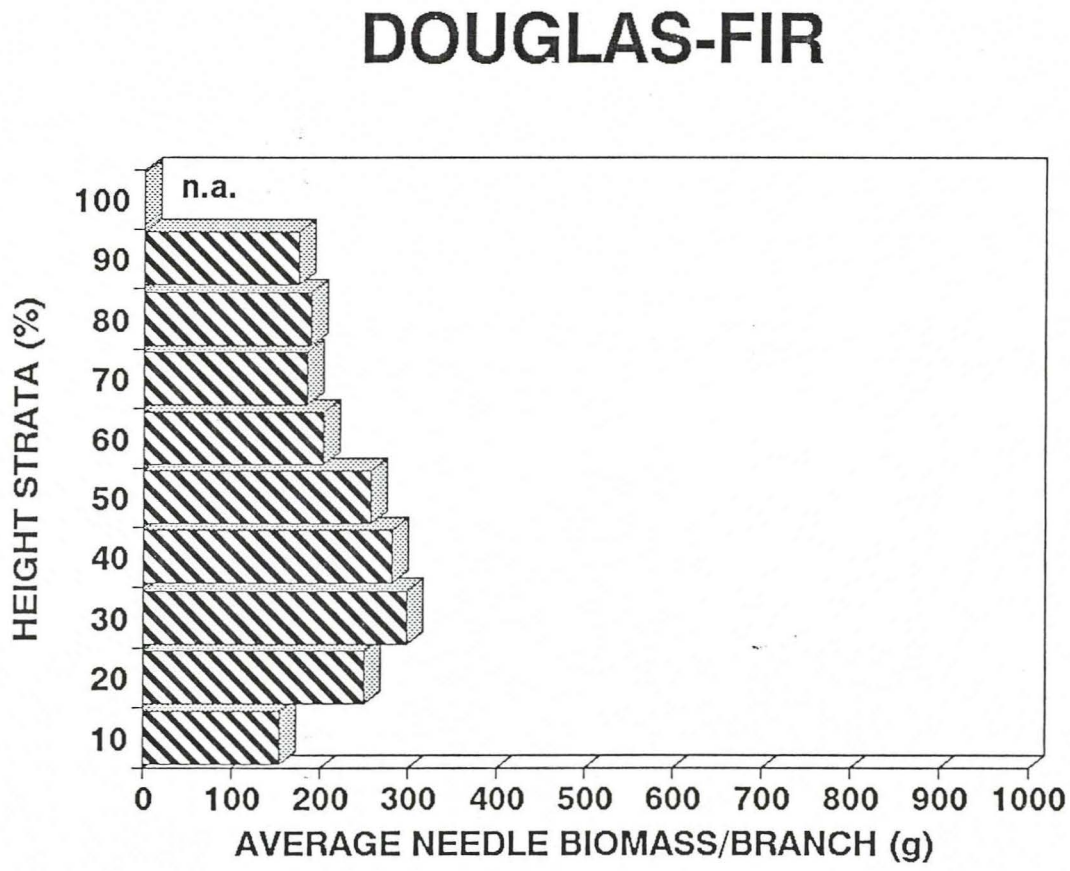

DOUGLAS-FIR
n.a.
100
90
80
70
60
50
40
30
20
10
HEIGHT STRATA (%)
0
100
200
300
400
500
600
700
800
900
1000
AVERAGE NEEDLE BIOMASS/BRANCH (g)

FIGURE 23.

WHITE FIR

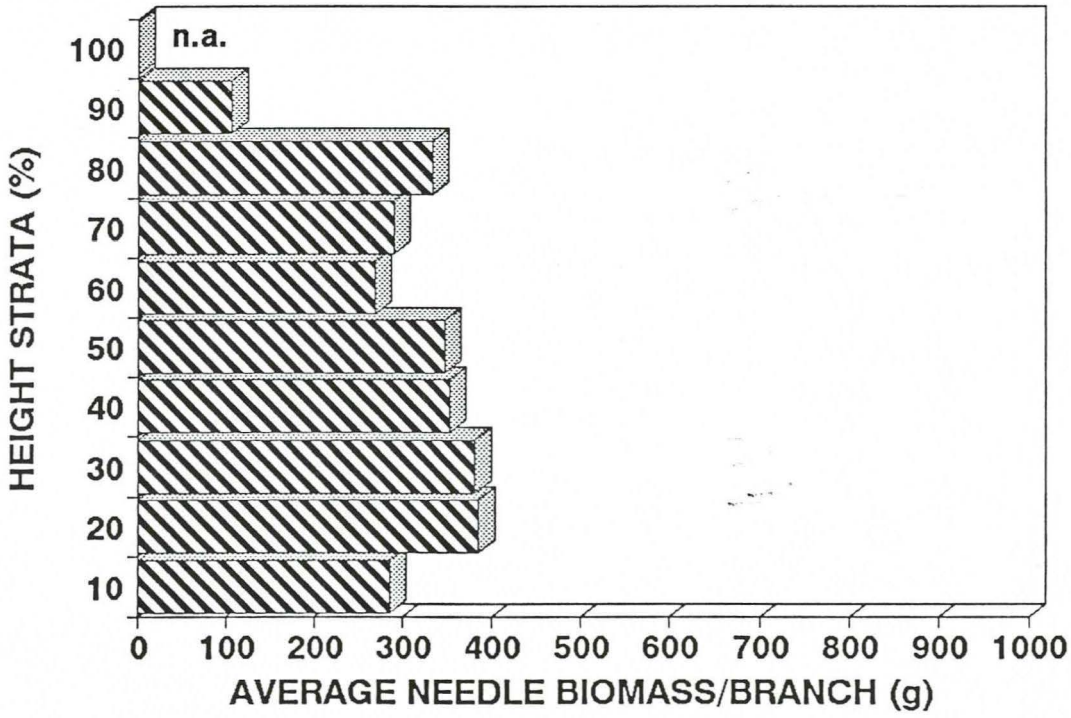


FIGURE 24.

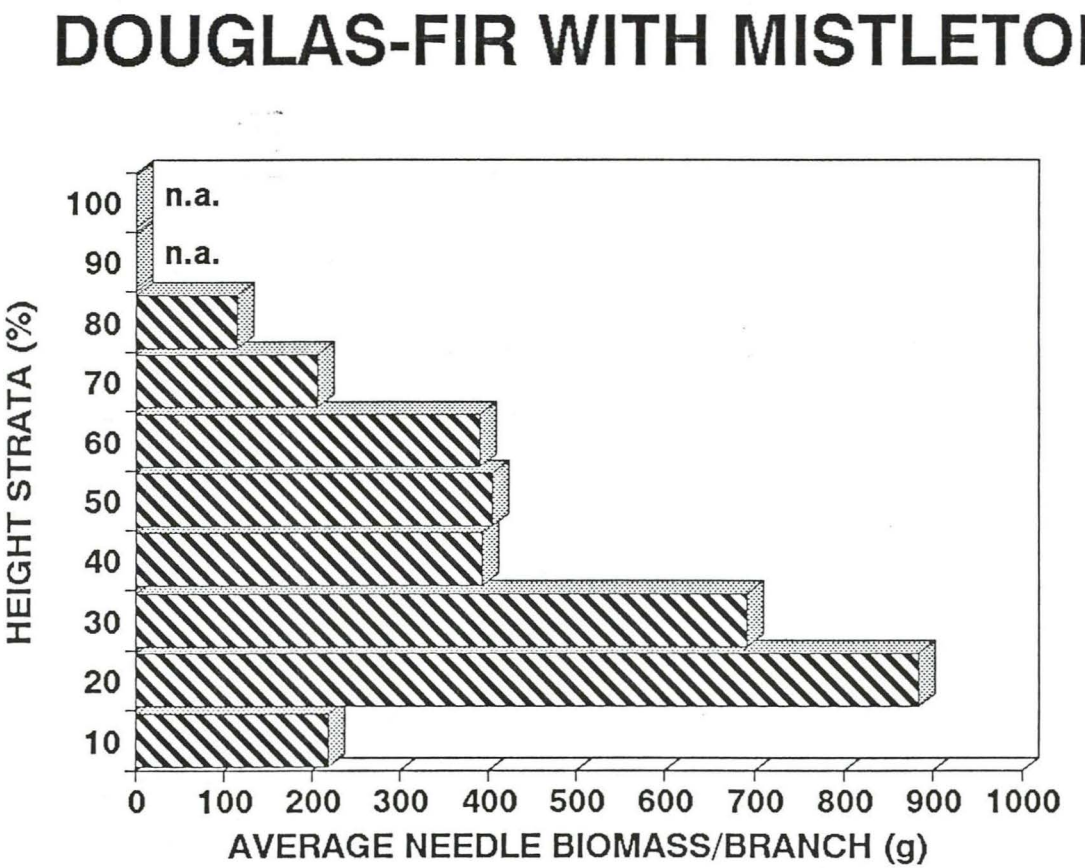

DOUGLAS-FIR WITH MISTLETOE
HEIGHT STRATA (%)
100
90
80
70
60
50
40
30
20
10
n.a.
n.a.
0
100
200
300
400
500
600
700
800
900
1000
AVERAGE NEEDLE BIOMASS/BRANCH (g)

FIGURE 25.

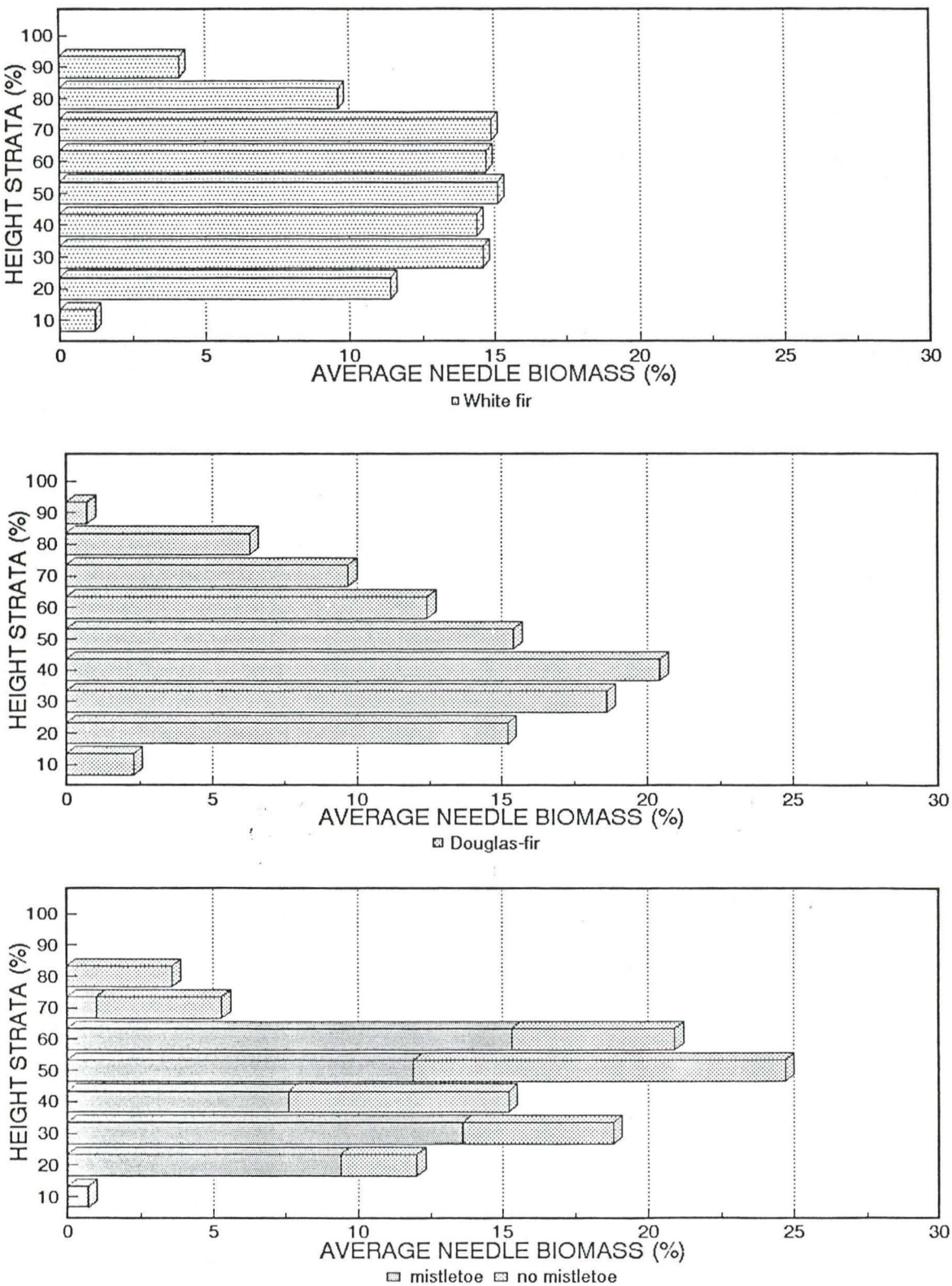
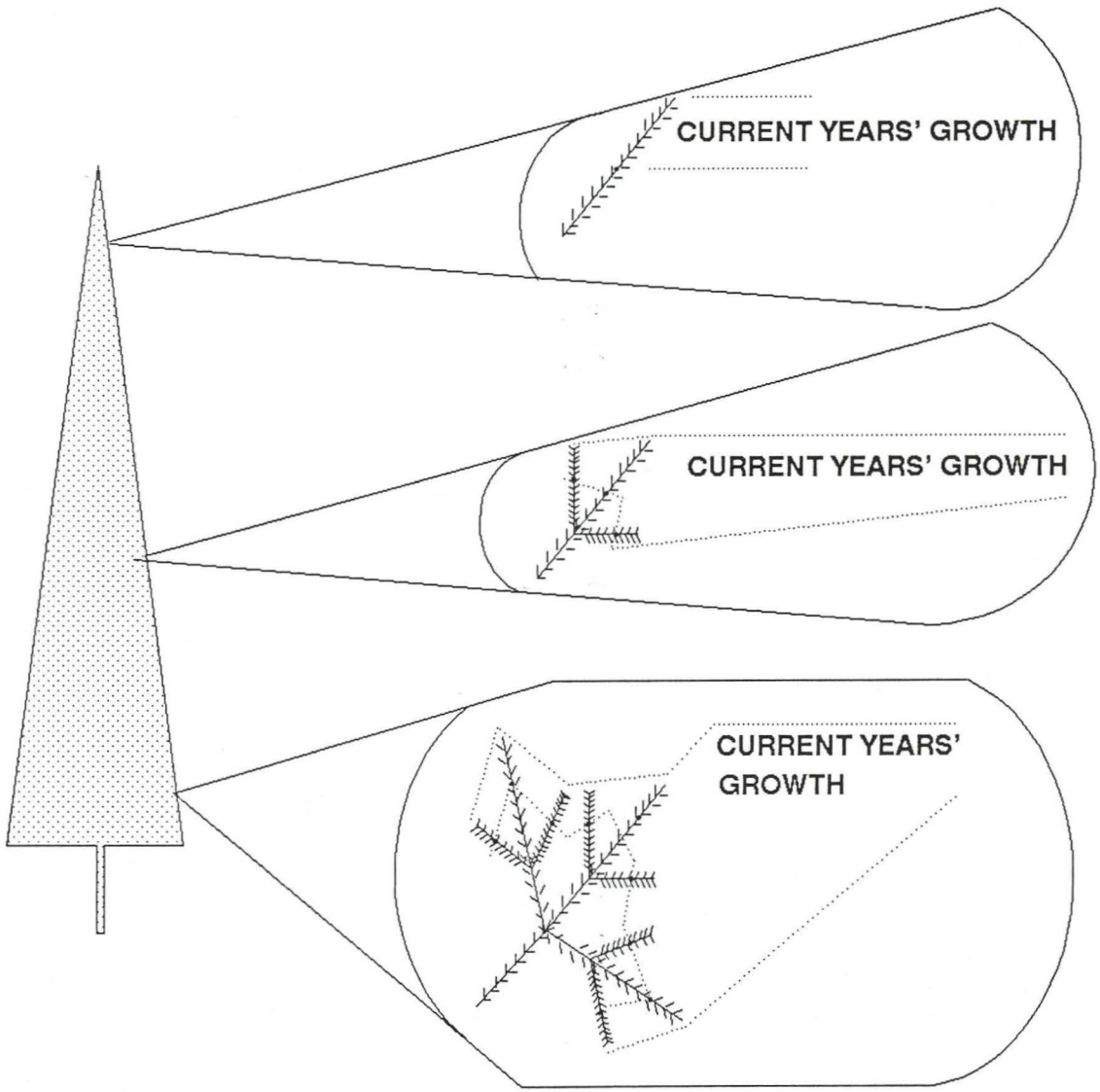

HEIGHT STRATA (%)
100
90
80
70
60
50
40
30
20
10
0
5
10
15
20
25
30
AVERAGE NEEDLE BIOMASS (%)
White fir
HEIGHT STRATA (%)
AVERAGE NEEDLE BIOMASS (%)
Douglas-fir
HEIGHT STRATA (%)
AVERAGE NEEDLE BIOMASS (%)
mistletoe
no mistletoe

FIGURE 26.



	DF	DF+dm	WF
CURRENT	16.4%	16.4%	15.9%
1 YR.	16.1%	16.4%	15.9%
REMAINING	67.5%	67.2%	68.2%

	DF	DF+dm	WF
CURRENT	17.1%	16.3%	16.2%
1 YR.	17.1%	16.3%	16.2%
REMAINING	65.8%	67.4%	67.6%

	DF	DF+dm	WF
CURRENT	19.6%	18.2%	20.5%
1 YR.	19.6%	18.2%	20.5%
REMAINING	60.8%	63.6%	59.0%

FIGURE 27.

DOUGLAS-FIR

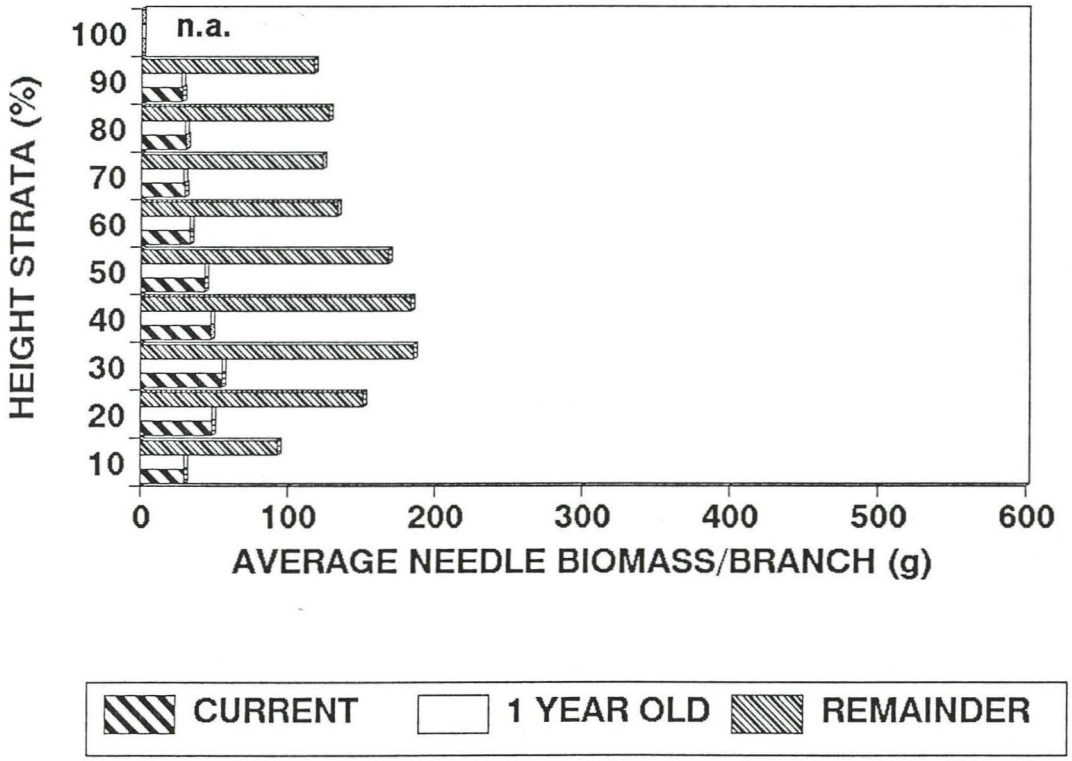


FIGURE 28.

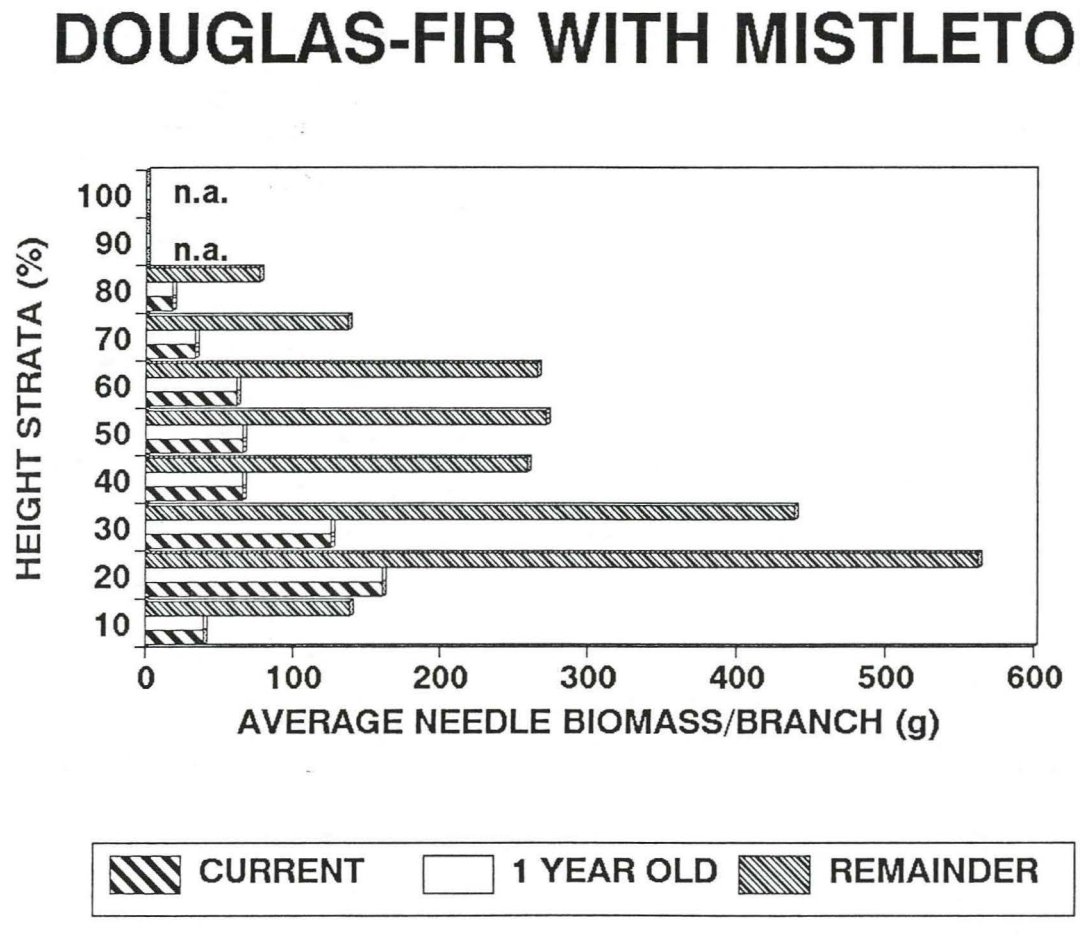

DOUGLAS-FIR WITH MISTLETOE
HEIGHT STRATA (%)
100
90
80
70
60
50
40
30
20
10
n.a.
n.a.
0
100
200
300
400
500
600
AVERAGE NEEDLE BIOMASS/BRANCH (g)
CURRENT
1 YEAR OLD
REMAINDER

FIGURE 29.

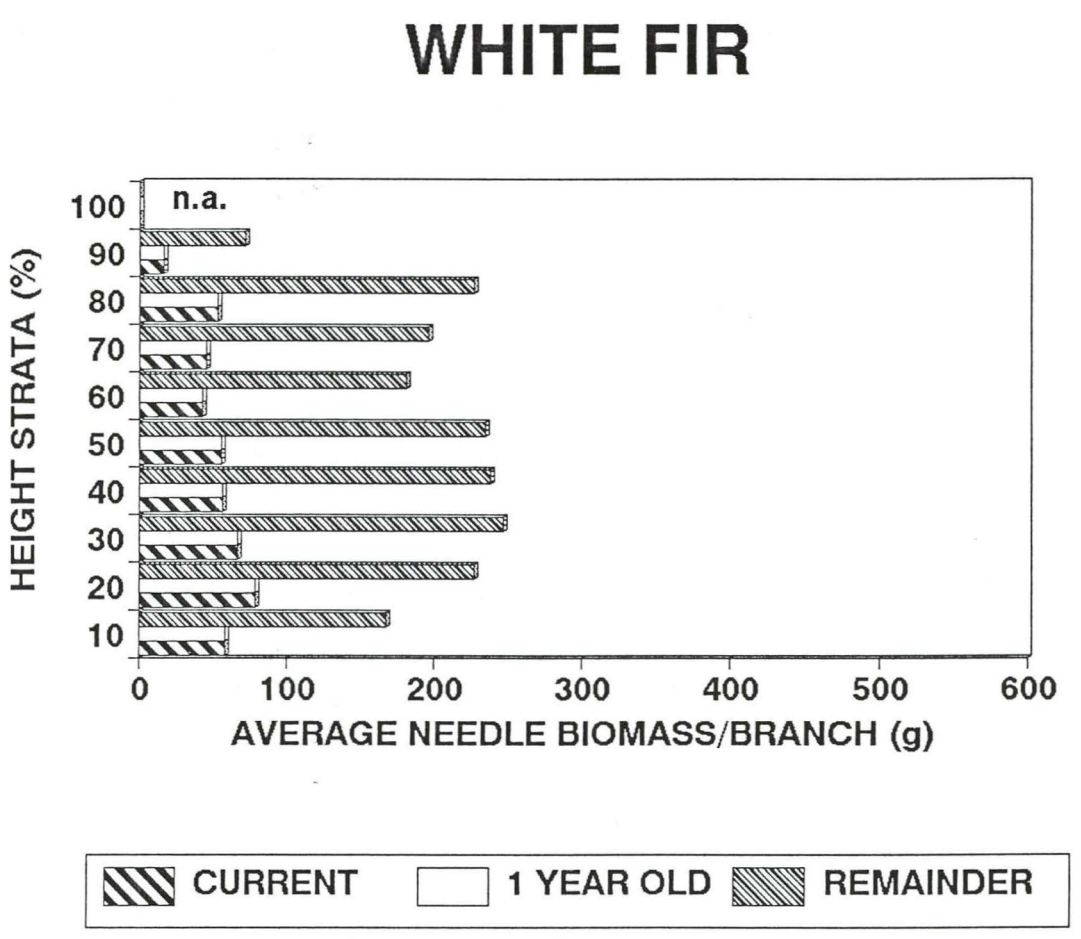
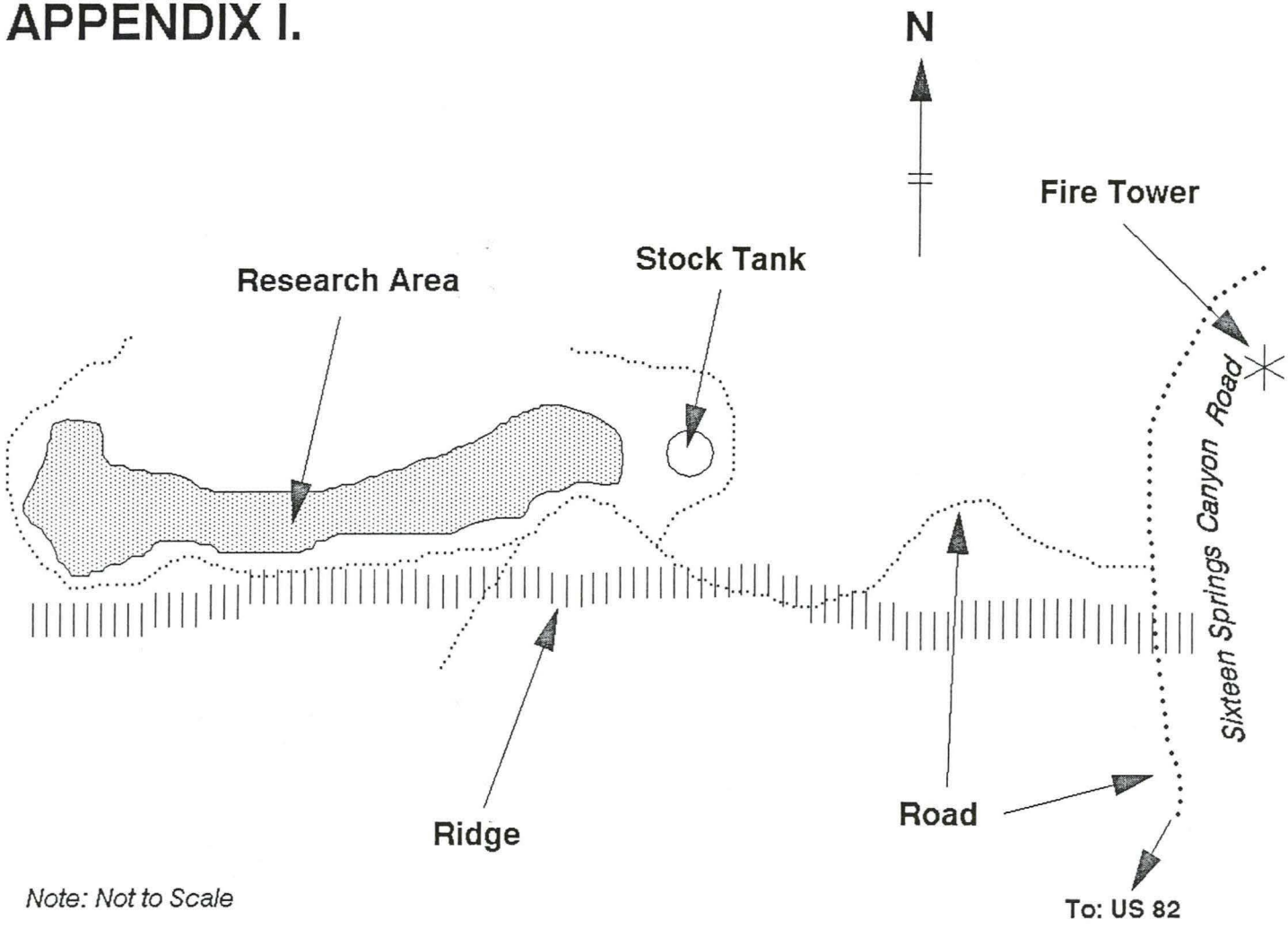

WHITE FIR
n.a.
100
90
80
70
60
50
40
30
20
10
HEIGHT STRATA (%)
0
100
200
300
400
500
600
AVERAGE NEEDLE BIOMASS/BRANCH (g)
CURRENT
1 YEAR OLD
REMAINDER

FIGURE 30.

APPENDIX I.



Note: Not to Scale

APPENDIX II. EXAMPLE OF SPREADSHEET LAY-OUT INCLUDING FORMULAS (This is an exact rendition of the way it was entered into Quatro-Pro vers. 2)

Branch	Bole diam	Branch diam	Daim^2	Prob.(1)	Cumm.(2) prob	Biom.	Est.(3) biom.	Branch no.	Height branch	Biom.(4) corr.	% of act.(5) biom.	% of Height(6)	
u	19.8	.198	.039204	.996579	.996579								)W
1		.0116	.000135	.003421	.003421	27.52	8045.461	1	1.63	29.49583	46.25	17.62	)H
2													)O
3													)R
4													)L
5													)
u	19.7	.197	.038809	.97964	.976289								
1		.0284	.000807	.02036	.02029	260.26	12827.04	2	2.15	260.261	73.74	23.24	
2													
3													
4													
5													
u	19.7	.197	.038809	.96635	.943715								
1		.0366	.001340	.033365	.032574	433.08	13295.28	3	2.27	372.8963	76.43	24.54	
2													
.	.	.	.	.	.	.	.	.	.	.	.	.	
.	.	.	.	.	.	.	.	.	.	.	.	.	
.	.	.	.	.	.	.	.	.	.	.	.	.	
u	6.2	.062	.003844	.764634	.057373								
1		.0152	.000231	.045958	.003448	78.95	22893.83	64	7.25	78.95	131.61	78.38	
2		.0120	.000144	.028644	.002149	34.99	16280.31	65	7.25	34.99	93.59	78.38	
3		.0198	.000392	.077983	.005851	142.13	24290.55	66	7.25	142.13	142.13	78.38	
4		.0204	.000416	.082781	.006211	135.71	21848.91	67	7.25	150.37	125.60	78.38	
5													
u	5.6	.0560	.003136	.629544	.036119								
1		.0225	.000506	.101628	.005831	179.22	30737.04	68	7.45	179.22	176.70	80.54	
2		.0125	.000156	.031367	.001800	41.86	23259.78	69	7.45	41.86	133.71	80.54	
3		.0288	.000829	.166508	.006014	265.76	44189.11	70	7.45	265.76	254.03	80.54	
4		.0188	.000353	.070952	.004071	128.40	31541.16	71	7.45	128.40	181.32	80.54	
5													
				TOTAL WEIGHT		14934.02							
UNITS	↑ cm	↑ m	↑ m^2			↑ gr	↑ gr		↑ m	↑ gr	↓ %	↓ %	

APPENDIX II. Continued (formulas)

(1) **PROBABILITY (per whorl):**

$$X_i = \frac{(DIAM)^2_i}{\sum_{(WHORL)} (DIAM)^2}$$

(2) **CUMULATIVE PROBABILITY:**

$$Y_i = Y_{U_{(previous\text{-}whorl)}} \cdot X_i$$

(3) **ESTIMATED BIOMASS (=Biomass when branch was not sampled):**

$$Z_i = \frac{(BIOMASS)_i}{Y_i}$$

(4) **CORRELATED BRANCH BIOMASS (Douglas-fir):**

$$A_i = 13736.02\,(DIAM_i) - 129.842$$

CORRELATED BRANCH BIOMASS (Douglas-fir + dwarf mistletoe):

$$A_i = 23470.43\,(DIAM_i) - 357.690$$

CORRELATED BRANCH BIOMASS (White fir):

$$A_i = 19783.64\,(DIAM_i) - 227.318$$

(5) **% OF ACTUAL BIOMASS:**

$$B_i = \frac{Z_i}{(TOTAL\text{-}WEIGHT)} 100\%$$

(6) **% OF HEIGHT:**

$$C_i = \frac{(HEIGHT\text{-}BRANCH_i)}{(TREE\text{-}HEIGHT)} 100\%$$

APPENDIX III. BIOMASS ESTIMATES USING EQUATIONS FROM MOEUR (1981)

DOUGLAS-FIR

ln(WT)=2.70587+2.08624ln(D)-1.07705ln(H)+0.69082ln(CL)-0.30885ln(A)-
-0.1421ln(TPA)+0.39924ln(DREL)

Douglas-fir 1	D	.205	m
	H	9.25	m
	CL	7.60	m
	A	87	year
	TPA	1401	t/ha
	DREL	0.404	
Douglas-fir 3	D	.367	m
	H	18.60	m
	CL	17.09	m
	A	76	year
	TPA	637	t/ha
	DREL	1.837	
Douglas-fir 4	D	.187	m
	H	10.60	m
	CL	9.30	m
	A	49	year
	TPA	255	t/ha
	DREL	1.190	
Douglas-fir 5	D	.253	m
	H	12.30	m
	CL	10.55	m
	A	57	year
	TPA	382	t/ha
	DREL	1.185	
Douglas-fir 13	D	.165	m
	H	11.25	m
	CL	11.10	m
	A	37	year
	TPA	764	t/ha
	DREL	0.675	
Douglas-fir 16	D	.23	m
	H	12.50	m
	CL	11.65	m
	A	63	year
	TPA	382	t/ha
	DREL	0.631	

APPENDIX III. CONT.

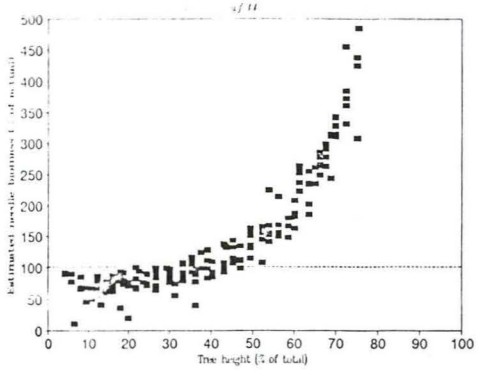
Douglas-fir 8 +m	D	.413	m
	H	18.80	m
	CL	13.75	m
	A	78	year
	TPA	255	t/ha
	DREL	1.113	
Douglas-fir 10 +m	D	.155	m
	H	10.60	m
	CL	9.75	m
	A	66	year
	TPA	382	t/ha
	DREL	0.887	
Douglas-fir 12 +m	D	.208	m
	H	11.90	m
	CL	8.75	m
	A	73	year
	TPA	637	t/ha
	DREL	0.805	
Douglas-fir 15 +m	D	.190	m
	H	9.30	m
	CL	8.80	m
	A	63	year
	TPA	382	t/ha
	DREL	1.456	
Douglas-fir 17 +m	D	.155	m
	H	6.85	m
	CL	5.80	m
	A	84	year
	TPA	509	t/ha
	DREL	0.176	
Douglas-fir 18 +m	D	.195	m
	H	10.05	m
	CL	7.85	m
	A	84	year
	TPA	891	t/ha
	DREL	0.572	

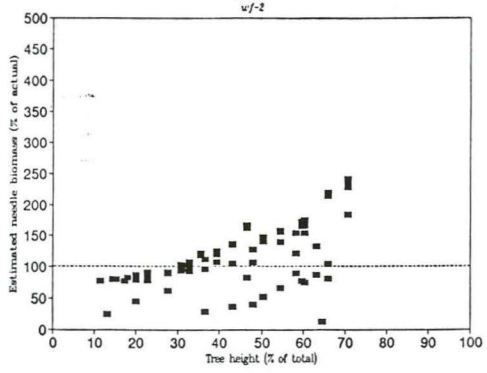
APPENDIX III. CONT.

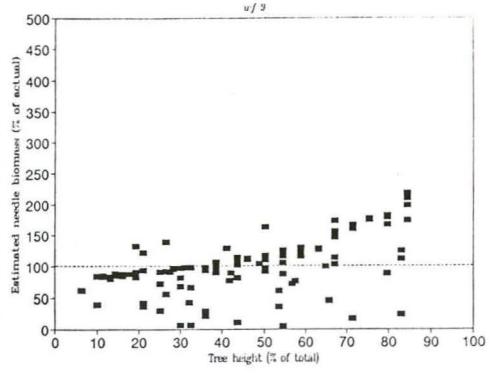
WHITE FIR (USE GRAND FIR)
ln(WT)=3.11508+2.08624ln(D)-1.07705ln(H)+0.69082ln(CL)-0.30885ln(A)-
-0.1421ln(TPA)+0.39924ln(DREL)

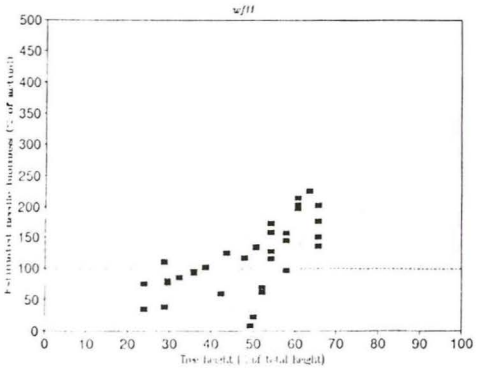
White fir 2	D	.182	m
	H	14.50	m
	CL	12.85	m
	A	60	year
	TPA	637	t/ha
	DREL	0.994	
White fir 6	D	.356	m
	H	13.80	m
	CL	12.95	m
	A	74	year
	TPA	637	t/ha
	DREL	1.748	
White fir 7	D	.232	m
	H	11.55	m
	CL	10.45	m
	A	64	year
	TPA	1019	t/ha
	DREL	0.829	
White fir 9	D	.229	m
	H	14.00	m
	CL	13.10	m
	A	60	year
	TPA	891	t/ha
	DREL	1.171	
White fir 11	D	.112	m
	H	7.10	m
	CL	5.40	m
	A	54	year
	TPA	637	t/ha
	DREL	0.231	
White fir 14	D	.486	m
	H	26.40	m
	CL	25.25	m
	A	78	year
	TPA	255	t/ha
	DREL	1.180	

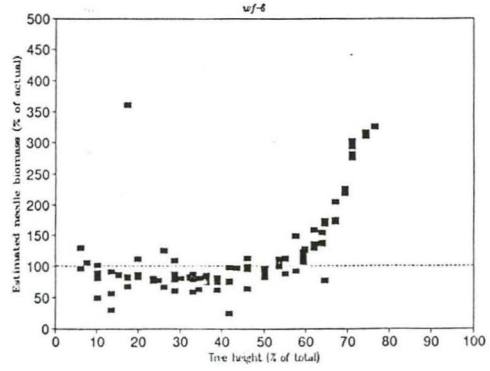
APPENDIX IV.

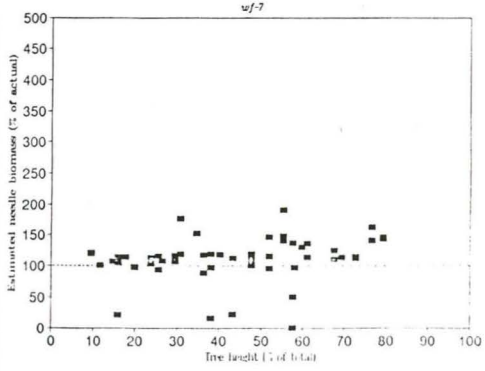

Estimated needle biomass (% of actual)
Tree height (% of total)


wf-2
Estimated needle biomass (% of actual)
Tree height (% of total)

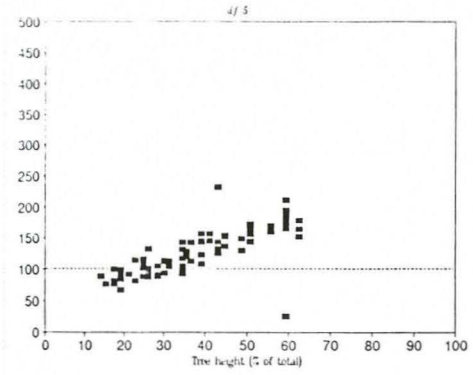

wf 9
Estimated needle biomass (% of actual)
Tree height (% of total)

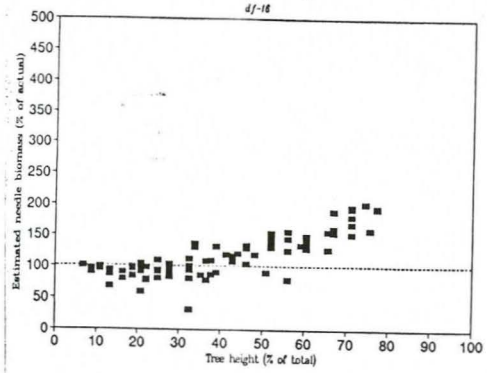

wf11
Tree height (% of total height)

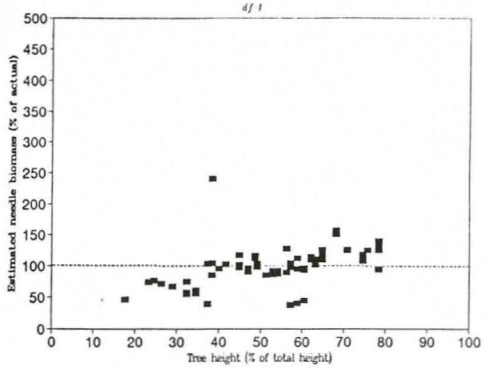

wf-6
Estimated needle biomass (% of actual)
Tree height (% of total)

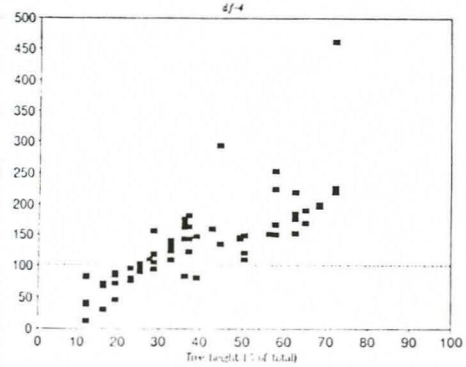

wf-7
Estimated needle biomass (% of actual)

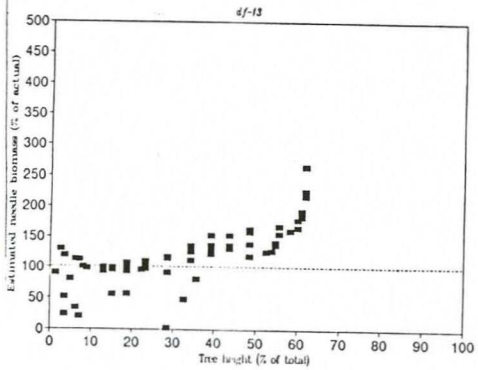
APPENDIX IV.

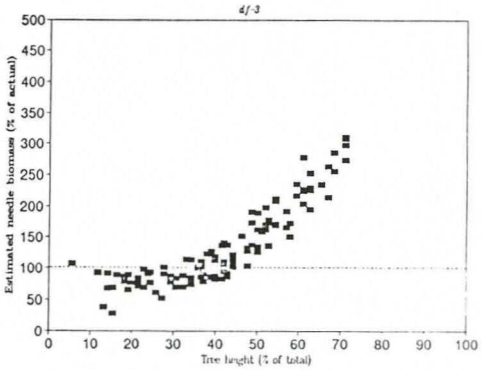

df 5
Tree height (% of total)


df-16
Estimated needle biomass (% of actual)
Tree height (% of total)

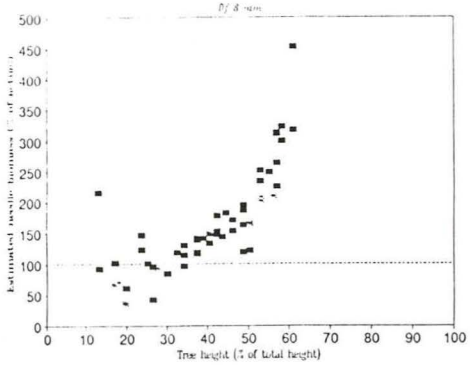

df 1
Estimated needle biomass (% of actual)
Tree height (% of total height)

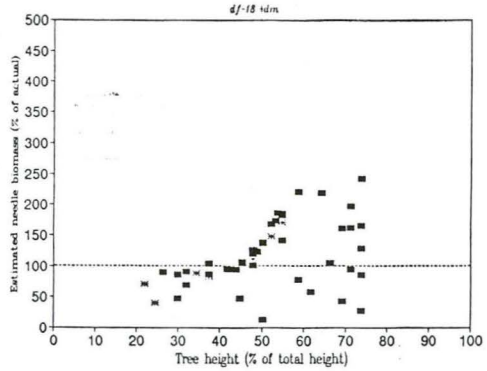

df-4

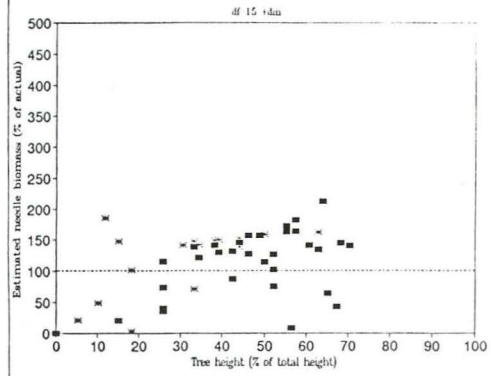

df-15
Estimated needle biomass (% of actual)
Tree height (% of total)

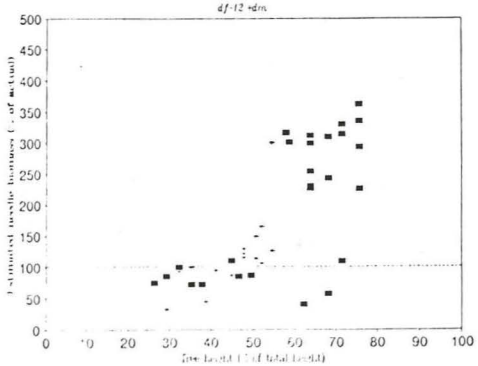

df-3
Estimated needle biomass (% of actual)
Tree height (% of total)

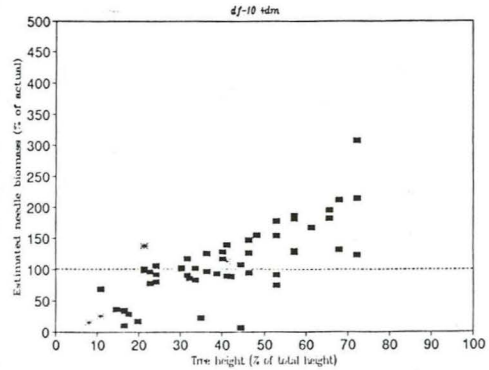
APPENDIX IV.

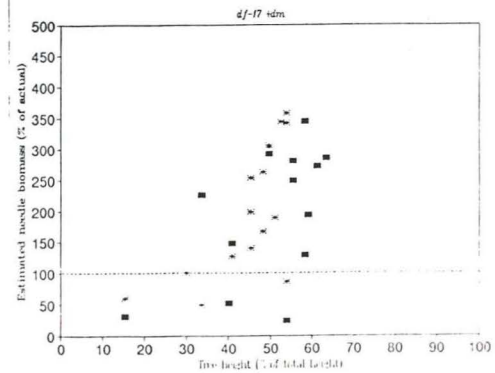

Estimated needle biomass (% of actual)
Tree height (% of total height)


df-18 +dm
Estimated needle biomass (% of actual)
Tree height (% of total height)


df-15 +dm
Estimated needle biomass (% of actual)
Tree height (% of total height)


df-12 +dm
Tree height (% of total height)


df-10 +dm
Estimated needle biomass (% of actual)
Tree height (% of total height)


df-17 +dm
Estimated needle biomass (% of actual)